Affordance-based control in running to catch fly balls

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THE AFFORDANCE OF CATCHABILITY IN RUNNING TO CATCH FLY BALLS

Dees Postma

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To my loving family.

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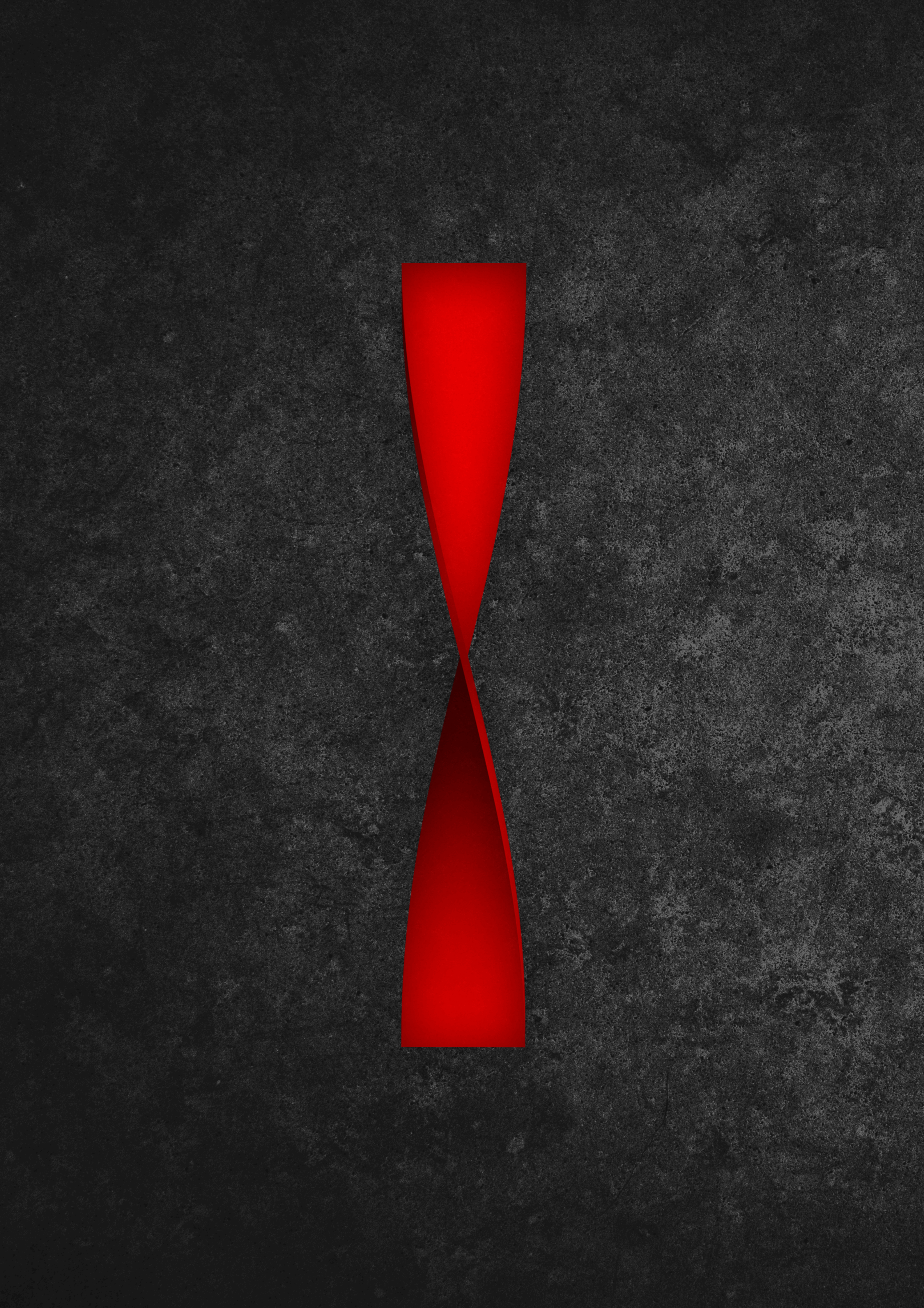

GENERAL INTRODUCTION

Dees B.W. Postma

The aim of this thesis is to further develop the concept of affordance-based control (Fajen, 2007), giving primacy to affordances, or action possibilities, in characterizing the visual guidance of action. As a case in point, this thesis considers the fly ball paradigm, which concerns the case of an outfielder running to make a catch in baseball. To fully understand how outfielders control their locomotor behavior while running to make an attempted catch, it is not only important to understand how behavior is controlled when a fly ball is catchable, but also when a fly ball is uncatchable. Anecdotally, outfielders' locomotor behavior can differ substantially depending on the catchability of a ball. Consider for instance the case in which an outfielder is presented with an uncatchable fly ball, instead of running to make an attempted catch, he or she might rather have a teammate make the catch. The concept of affordance-based control deals with this phenomenon, aiming to capture not only how agents control their behavior when an action is afforded, but also when an action is not afforded (hence 'affordance-based control'). Fajen developed the concept of affordance-based control by considering the task of braking a car to a safe stop (Fajen, 2005a, 2005c, 2005b, 2007). In this thesis it will be examined whether the framework of affordance-based control can also be applied to the context of catching fly balls. In doing so, this thesis should be read as an effort to advance the concept of affordance-based control within the field of Ecological Psychology.

INTRODUCTION

Central to the concept of affordance-based control is the concept of affordances. The concept of affordances was originally put forward by Gibson (1966, 1979)[1]. A popular definition of this concept reads as follows: "The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes,* either for good or ill" (Gibson, 1979). From this definition, it is important to note that the concept of affordances is relational. Affordances capture the relation between behaviorally relevant properties of the environment and behaviorally relevant properties of the agent's action system (Warren, 1984). As a shorthand definition one could say that affordances are possibilities for action, or simply *action possibilities*. Translating this to the present context: Catching is afforded to an outfielder that is capable of getting to the right place in the right time to intercept the ball[2]. Thus, the affordance of catchability is determined by relevant properties of the agent's action system on the one hand (e.g. maximal running speed and -acceleration) and by relevant properties of the ball's trajectory on the other hand (e.g. flight time and projection angle). Together, these agent-environment properties relate to provide the affordance of catchability.

For an agent to act (adequately), accurate perception of affordances is key. This rings true for countless human endeavors (Fajen, 2007; Gibson, 1979; Harrison, Turvey, & Frank, 2016; Michaels & Carello, 1981; Turvey, Shaw, Reed, & Mace, 1981). Crossing the street, overtaking a lorry, braking a car to a safe stop and running to make a catch in baseball are just some examples, all of which necessitate an agent to be aware of his or her affordances. Yet, the influence of affordances on control of behavior is typically overlooked (Barsingerhorn, Zaal, Smith, & Pepping, 2012; Fajen, 2007; Stoffregen, 2000). That is not to say that affordances have not been extensively studied (e.g. Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Cesari, Formenti, & Olivato, 2003; Cesari & Newell, 1999, 2000; Mark, 1987; Newell, McDonald, & Baillargeon, 1993; Warren, 1984; Warren & Whang, 1987). Rather, affordance-theory and control-theory have long been studied in isolation from one another (e.g. Warren, 1988). The concept of affordance-based control breaks with this practice and aims to unite these two prongs of perception-action research into one comprehensive framework (Fajen, 2007). In this, Fajen's seminal work on the braking paradigm (Fajen, 2005a, 2005c, 2005b, 2007) forms the fundament for the concept of affordance-based control as it is known today.

To push the development of affordance-based control, the fly ball paradigm will be the primary focus of this dissertation. The fly ball paradigm provides a suitable context for the development of the concept of affordance-based control for a number of reasons, one of which is the wide availability of suitable models on locomotor control (e.g. Chapman, 1968; McBeath, Shaffer, & Kaiser, 1995; McLeod, Reed, & Dienes, 2006; Michaels & Oudejans, 1992). But then, what is it exactly that needs to be controlled? The fly ball paradigm concerns the case of an outfielder running to make a catch in baseball. Getting to the right place in the right time to intercept a fly ball is a nontrivial task, characterized by stringent spatial and temporal demands (Adair, 2002). This has inspired scientists to marvel and theorize about this amazing human feat (most notably Chapman, 1968, but see also: Marken, 2001; McBeath

[1] For a precursor of the concept of affordances see: Gibson, 1958.

[2] It has been suggested (e.g. Fink et al., 2009; Michaels & Oudejans, 1992) that intercepting a fly ball is an action consisting of two phases: A *locomotion-phase* in which the outfielder moves to get to the right place in the right time, and a *catching-phase* in which the outfielder makes the actual catch. Throughout this thesis, only the locomotion-phase will be considered.

et al., 1995; McLeod et al., 2006; Michaels & Oudejans, 1992; Shaffer, Krauchunas, Eddy, & McBeath, 2004). Yet, most studies that have looked at locomotor control in running to catch fly balls have done so in isolation of the affordance of catchability, that is: most studies only considered locomotor control for fly balls that were catchable. As such, existing (*information-based control*) accounts are only valid for fly balls projected within the catchable range of the outfielder, thereby ignoring the potential effect that affordances might have on locomotor control (Fajen, 2007). This thesis sets out to advance a control strategy for running to catch fly balls that puts the affordance of catchability centerstage in characterizing outfielders' locomotor behavior.

For the remainder of this introductory chapter, a theoretical overview on *information-based control* will be provided, which has (long) been the prominent approach for theorizing about motor control within the field of Ecological Psychology. Thereafter, the problem of *action boundaries* will be introduced, which will lead to a formal introduction of the concept of *affordance-based control*. This introduction will be given by considering the braking paradigm, a quintessential paradigm in Ecological Psychology by means of which the concept of affordance-based control has been originally developed (Fajen, 2007). Then, the fly ball paradigm will be introduced, paying special attention to the potential merits of affordance-based control over information-based control in theorizing about motor control in running to catch fly balls. Finally, this chapter will conclude with an outline of the present thesis.

INFORMATION-BASED CONTROL

For decades, the prominent framework for characterizing an assortment of (visually guided) actions within the field of Ecological Psychology has been the information-based control framework (e.g. Chapman, 1968; Fajen, 2001, 2007; Fajen & Warren, 2004; Kim & Turvey, 1999; Kim, Turvey, & Carello, 1993; Lee, 1976; McBeath et al., 1995; McLeod et al., 2006; Michaels & Oudejans, 1992; Peper, Bootsma, Mestre, & Bakker, 1994; Wann & Land, 2000; Yilmaz & Warren, 1995). From the information-based control perspective, control of visually guided action is conceptualized as a process of error-nulling. The fly-ball paradigm is no exception in that (Chapman, 1968; McBeath et al., 1995; McLeod et al., 2006; Michaels & Oudejans, 1992). In 1968, physicist Neville Chapman suggested that outfielders in baseball might be able to utilize changes in the elevation angle of the ball to guide locomotor behavior (Chapman, 1968). For fly balls approaching an outfielder head on[3], Chapman showed mathematically that the rate of change of the tangent of the elevation angle of the ball ($\mathrm{d}(\tan\alpha)/\mathrm{dt}$) is constant for outfielders running at the only constant velocity that would lead them to the right place in the right time to intercept the ball. Conceived as such, an outfielder should strive to keep $\mathrm{d}(\tan\alpha)/\mathrm{dt}$ constant by controlling running speed. An increase in $\mathrm{d}(\tan\alpha)/\mathrm{dt}$ signifies that a batted ball will fly overhead as long as current running speed is maintained while the opposite holds true for decreasing values of $\mathrm{d}(\tan\alpha)/\mathrm{dt}$. Thus, an outfielder might control locomotor velocity to get to the right place in the right time by correcting for non-constancies in $\mathrm{d}(\tan\alpha)/\mathrm{dt}$. This locomotor strategy has become known as the Chapman strategy.

[3] For fly balls hit to the side, Chapman suggested that outfielders are required to also keep the bearing angle with the ball constant (Chapman, 1968). In the present thesis however, the focus will solely be on the case of fly balls approaching fielders head on.

For the Chapman strategy to serve as a basis for locomotor control in running to catch fly balls, the perceptual system must be able to pick up non-constancies in $\mathrm{d}(\tan\alpha)/\mathrm{dt}$, which is according to the Chapman strategy the information relevant to catching fly balls. Without sensitivity to changes in $\mathrm{d}(\tan\alpha)/\mathrm{dt}$, outfielders would be unable to gauge the sufficiency of their current locomotor velocity. When outfielders track the ball with their gaze, $\mathrm{d}(\tan\alpha)/\mathrm{dt}$ might be directly picked up from the gaze angle with the ball. A more general solution, also useful when gaze is not directed at the ball, can be found in the Optical Acceleration Cancellation (OAC) strategy (Michaels & Oudejans, 1992). The OAC-strategy is highly similar to the Chapman strategy, but captures its rationale in terms of the optical position of the ball, which is the projection of the ball on a planar image plane. When $\mathrm{d}(\tan\alpha)/\mathrm{dt}$ is constant, the rate of change of the optical position of the ball is constant as well. Thus, keeping constant the optical velocity of the ball will lead a fielder to the interception location with the ball in time. As keeping optical velocity constant is equivalent to nulling optical acceleration, this strategy has become known as the Optical Acceleration Cancellation strategy[4]. Because the OAC-strategy provides a more general solution to the case of running to catch fly balls, the OAC-strategy will be used to refer to the control principles originally put forward by Chapman.

Scientific inquiry showed that outfielders' locomotor patterns are consistent with the use of the OAC-strategy. For fly balls that are successfully intercepted, outfielders display locomotor behavior that leads to the nulling of optical acceleration for the largest part of their running movement (Dienes & Mcleod, 1996; Dienes & McLeod, 1993; Fink, Foo, & Warren, 2009; Michaels & Oudejans, 1992). In fact, it has been shown that locomotor patterns are not merely coincidental to the use of optical acceleration, but are in fact strongly related to the use of optical acceleration (Fink et al., 2009). In an experiment by Fink and colleagues (2009), participants were faced to catch fly balls in virtual reality. By applying mid-flight perturbations to the (virtual) ball trajectories, it could be examined how participants responded to sudden changes in the vertical motion of the ball. It was found that participants adjusted their locomotor velocity in a manner that was consistent with the use of the OAC-strategy[5]. Further evidence in favor of the OAC-strategy stems from studies scrutinizing the gaze behavior of outfielders running to make a catch. Outfielders are shown to maintain continuous visual contact with the ball while running to make an attempted catch (e.g. Oudejans, Michaels, Bakker, & Davids, 1999), even for fly balls that they perceive to be uncatchable (see also Chapter 2). This was found to be the case for fly balls projected in front of- and behind of the initial position of the outfielder.

The principle of error-nulling in control of visually guided action is characteristic for information-based control strategies (Chapman, 1968; Kim & Turvey, 1999; Lee, 1976; Peper et al., 1994). Information-based control theories have been formulated for numerous human endeavors: Braking a car to a safe stop (Kim et al., 1993; Lee, 1976; Yilmaz & Warren, 1995); steering to a goal (Fajen, 2001; Kim & Turvey, 1999; Wann & Land, 2000), following a lane

[4] The OAC-strategy considers the special case of fly balls approaching a fielder head on. For fly balls heading off to the side, alternative strategies exist, accounting not only for fore-aft movements, but also for lateral running movements in fly-ball interception. Most notable are the Linear Optical Trajectory (LOT) strategy (McBeath et al., 1995); the segmented Linear Optical Trajectory (SLOT) strategy (Shaffer et al., 2004); the Generalized Optical Acceleration Cancellation (GOAC) strategy (McLeod et al., 2006) and the Constant Optical Velocity strategy (COV) strategy (Marken, 2001; Shaffer, Marken, Dolgov, & Maynor, 2013, 2015). While the latter strategy would also be able to account for control in intercepting objects that approach an agent head on, its use has not yet been tested for the case of running to catch fly balls.
[5] Note that for this study all fly balls were 'projected' within the catchable range of the participant.

(Duchon & Warren, 2002); intercepting moving objects (Fajen & Warren, 2003, 2004, 2007) and of particular interest for the present case, intercepting fly balls (Chapman, 1968; McBeath et al., 1995; McLeod et al., 2006; Michaels & Oudejans, 1992). The hallmark trait of such control theories is the identification of some invariant optical variable that specifies whether the acting organism's (i.e. *actor*'s) actions are sufficient to meet the intended goal. In case of the OAC-strategy, this invariant optical variable is optical acceleration. Either optical acceleration is zero, specifying that an outfielder's locomotor velocity is sufficient to get to the interception location in time or optical acceleration is nonzero (either positive or negative) specifying that an outfielder's current locomotor velocity is not sufficient to get to the interception location in time. The rationale for developing the concept of affordance-based control stems from the latter situation: When an outfielder is running at a velocity that is insufficient to get to the interception location in time, it is unclear from just the magnitude of optical acceleration whether it is still within the outfielder's action possibilities to make the catch (see also Chapter 3). Without reference to what an outfielder can or cannot do, optical acceleration is not indicative of the affordances of the situation. This issue, known as the *problem of action boundaries*, is not unique to the OAC-strategy, but is characteristic for all information-based control strategies (Fajen, 2007).

THE PROBLEM OF ACTION BOUNDARIES

While the OAC-strategy has inspired many scientific endeavors and has greatly improved our understanding of locomotor control in running to catch fly balls, it appears to be fundamentally incompatible with the concept of affordances (see also Chapter 3). From the use of optical acceleration, an outfielder can only gauge the *sufficiency* of his or her current running efforts in making an attempted catch. Either running speed is sufficient, specifying that the outfielder will get to the right place in the right time to make a catch, or running speed is insufficient, specifying that the outfielder will not reach the interception location with the ball in time if current running speed is maintained. The first scenario, in which running speed is sufficient, is unambiguous with respect to the affordance of catchability: The ball can be successfully intercepted given that current running speed can be maintained. The latter scenario however, in which current running speed is insufficient, is not unambiguous with respect to the affordance of catchability: It will depend on the locomotor abilities of the outfielder whether the running velocity that is required to effectively null optical acceleration can still be attained (in time). This is known as the problem of action boundaries. While action boundaries are shown to have a profound effect on the way behavior is controlled (Fajen, 2005a, 2005c, 2005b, 2007, 2013), this is left unaccounted for by the OAC-strategy.

The influence of action boundaries, and thereby the affordance of catchability, on locomotor control in running to catch fly balls can be made tangible by considering two typical situations often encountered in baseball. First, consider a scenario in which an outfielder is presented with a fly ball that is absolutely uncatchable. Based on the principles of the OAC-strategy one would expect the outfielder to simply start running in order to cancel out optical acceleration. In practice however, outfielders are very well able to judge the (un)catchability of such a fly ball and act accordingly. As such, when an outfielder perceives a fly ball to be definitively uncatchable, he or she might initiate a defensive maneuver and instead have a teammate make the attempted catch. A more subtle example in which the affordance of catchability might influence locomotor behavior might be observed when an outfielder is running at the right speed, at near maximal velocity, to intercept the ball. In this scenario, the outfielder might be inclined to increase his or her running speed just a little further to create a safe margin in order to account for small and unexpected changes in the ball's trajectory. Both scenarios illustrate the potential effect of the affordance of catchability on locomotor behavior in running to catch fly balls. Information-based control strategies are unable to account for the influence that such action (im)possibilities might have on behavior. The concept of affordance-based control aims to remedy this.

THE CONCEPT OF AFFORDANCE-BASED CONTROL

Fajen developed the concept of affordance-based control to address the problem of action boundaries; by studying the task of braking a car to a safe stop, he showed that motorists are sensitive to the strength of the brake of a car and that behavior is controlled accordingly (Fajen, 2005a, 2005c, 2005b). These findings ultimately led to the formalization of the affordance-based control framework (Fajen, 2007). Over the following paragraphs, the concept of affordance-based control will be introduced. This will be done by following Fajen in his footsteps, considering the braking paradigm. The merits of affordance-based control within the context of braking will be highlighted and the challenges for generalizing its principles to the fly ball paradigm will be discussed.

In braking a car to a safe stop, the dominant (information-based) account on the visual guidance of braking has been known as the $\dot{\tau}$-strategy (Lee, 1976). This strategy holds that in order to come to a safe stop, motorists should strive to keep optical invariant $\dot{\tau}$ at -0.5. When $\dot{\tau}$ is greater than -0.5, the current rate of deceleration is greater than the rate of deceleration needed to come to a safe stop, leading the vehicle to come to an early stop. Conversely, when $\dot{\tau}$ is smaller than -0.5, the current rate of deceleration is smaller than the rate of deceleration needed to come to a safe stop, leading the vehicle to crash if the rate of deceleration is not increased. As such, braking behavior can be controlled by striving to keep $\dot{\tau}$ (close to) -0.5.

While many empirical studies have implicated the use of $\dot{\tau}$ in the visual guidance of braking (e.g. Kim et al., 1993; Lee, 1976; Yilmaz & Warren, 1995), the $\dot{\tau}$-strategy is unable to account for behavior that is contingent on the perception of affordances. Because the strength of the brake of the car is not accounted for, the $\dot{\tau}$-strategy is unable to differentiate between situations in which safe braking is (still) afforded and situations in which safe braking is not (any longer) afforded. As such the $\dot{\tau}$-strategy is mute on the concept of affordances in braking a car to a safe stop in much the same way as the OAC-strategy is mute on the concept of affordances in the case of running to catch a fly ball. To address this issue, Fajen proposed an alternative account for the visual guidance of braking: Rather than nulling the error in $\dot{\tau}$, Fajen proposed that the ratio of *ideal deceleration* (d_{ideal}) over *maximal deceleration* (d_{max}) should be kept below 1. In this, ideal deceleration is the rate of deceleration that would bring a car to a safe stop without having to make additional braking adjustments and maximal deceleration is the maximal rate of deceleration that can be achieved. By attending to the ratio of d_{ideal} over d_{max} motorists can control braking behavior relative to their action boundaries. When ideal deceleration is smaller than maximal deceleration, the motorist is (still) able to brake the car to a safe stop, meaning that stopping is (still) afforded. Conversely, when ideal deceleration is greater than maximal deceleration, the motorist is no longer able to safely brake the car to a safe stop, meaning that safe stopping is no longer afforded. In the latter case, the motorist might try to avoid collision by steering away from the impending obstacle, rather than by frantically slamming the brakes. Thus, to ensure safe braking, the actor only has to make sure that the ratio of d_{ideal} over d_{max} remains (well) below 1.

Fajen showed that the ratio of d_{ideal} over d_{max} is optically available to motorists (Fajen, 2005a) and that motorists take their action boundaries into account in braking a car to a safe stop (Fajen, 2005a, 2005c). A prime example of the latter finding stems from an experiment in which participants were required to perform a virtual braking task (Fajen, 2005c). Participants viewed a simulated scene in which they approached a row of stop signs along a linear path. Using a hand-operated brake, the rate of deceleration could be controlled. Participants were encouraged to brake as they would do in every-day life to bring a car to a safe stop. The maximal rate of deceleration (i.e. the strength of the brake) was manipulated as a between-subjects factor. When considering the value for ideal deceleration at braking onset, significant differences were found between groups: Participants that were equipped with a weaker brake started braking at lower values for ideal deceleration than participants equipped with a stronger brake. When, however, ideal deceleration at braking onset was expressed in intrinsic units as a percentage of the maximal strength of the brake, the significant differences observed between groups were no longer present: All participants started braking when the ideal rate of deceleration was approximately at 50% of the maximal rate of deceleration. This is an interesting finding as it supports the notion that motorists are sensitive to their action boundaries and take their action boundaries into account in visually guided braking. Another convincing piece of evidence stems from the finding that (in a similar braking task), participants showed to make more braking adjustments when they were close to their action boundary than when they were far off from maximal deceleration (Fajen, 2005c). This finding is interesting because in analyzing the data, only data points in which the rate of deceleration was equal to the ideal rate of deceleration were used, meaning that motorists did not have to increase braking pressure to come to a safe stop, but did so anyway in order to keep ideal deceleration (well) below their maximal deceleration.

The merits of the concept of affordance-based control in the context of the braking paradigm are clear: With this novel concept in hand, it is possible to explain how motorists might perceive whether safe braking is still afforded. Still, a number of issues remain. First off, in the virtual braking tasks presented by Fajen, the action boundary was obvious, when the brake was fully depressed, the maximal rate of deceleration was achieved. Yet, for many other tasks in everyday life, this action boundary is not (as) easily identified. Consider for instance the case of an actor crossing the street in front of an oncoming vehicle. Is the actor in this scenario limited in his or her action possibilities by the maximal running speed that can be achieved, or rather by the maximal running acceleration that can be achieved? Or would it rather be a particular combination of the two kinematic measures? In the fly ball paradigm, the paradigm under study here, the action boundary for running to catch a fly ball is not obvious either, which renders the formalization of an affordance-based control strategy challenging. Furthermore, in his seminal papers, Fajen used a brake that allowed actors to access the maximal rate of deceleration instantaneously. In everyday life, whether it is in running to make a catch, in crossing a street or even in braking a car to a safe stop, actors are typically unable to reach their full potential instantaneously (see also Fajen, 2008). In real life braking for instance, it would take a moment to achieve the maximal rate of deceleration. Another issue pertaining to affordance-based control that will be addressed in this thesis is a more conceptual one; Fajen's original proposal on affordance-based control provides no specific account on how motorists control their braking behavior within the limits of their action possibilities. Instead, motorists are left with an infinite range of possible motor behaviors that satisfy the intended goal. That is to say, cautious drivers might brake conservatively in order to come to a safe stop, while motorists that favor speed might instead be inclined to brake more aggressively. From the concept of affordance-based control as formalized by Fajen, there is no way to collapse possibility into actuality. Which renders it very difficult to make predictions about actors' braking behavior from an affordance-based perspective (however, see Harrison et al., 2016).

To further develop the concept of affordances and to address the issues mentioned above, this thesis focusses on the fly ball paradigm. The fly ball paradigm is very well suited to further develop the concept of affordance-based control and to address the issues mentioned above for a number of reasons. First of all, the fly ball paradigm has been studied intensively in terms of locomotor control (e.g. Chapman, 1968; Fink et al., 2009; McBeath et al., 1995; McLeod, Reed, & Dienes, 2002; McLeod et al., 2006; Shaffer & McBeath, 2002; Shaffer, McBeath, Krauchunas, & Sugar, 2008; Shaffer, McBeath, Roy, & Krauchunas, 2003). Second, the fly ball paradigm allows for a close(r) examination of action boundaries. In braking, the (implicit) assumption was that actors could achieve the maximal rate of deceleration instantly (Fajen, 2005a, 2005c, 2005b, however, see Fajen, 2008). For many everyday life behaviors, including braking a car to a safe stop, it seems unlikely that actors are able to access the limit of their action capabilities instantly. Thus, rather than having a fixed action boundary, outfielders in baseball might have action boundaries (and thus action possibilities) that evolve over time. Here, this presumption will be explicitly addressed. Finally, through the fly ball paradigm, attention will be dealt to the role of control within the concept of affordance-based control. As mentioned above, the affordance-based control strategy for braking a car to a safe stop, as originally proposed by Fajen (2007), lacks a specific account of how the breath of possible braking strategies can be collapsed into a particular outcome (Harrison et al., 2016).

THESIS OUTLINE

The aim of this thesis is to develop an affordance-based control strategy for fly-ball catching, both to increase the understanding of locomotor control in catching fly balls and to further develop the framework of affordance-based control. Chapter 2 of this thesis examines the gaze behavior that outfielders display while running to catch fly balls. Special attention is dealt to the extent to which outfielders track the ball throughout its trajectory during an attempted catch. Chapter 3 examines whether the OAC-strategy, the dominant account on locomotor control in fly-ball catching, might serve as the basis for perceiving the affordance of catchability. From the use of the OAC-strategy, it is predicted that outfielders would only judge a fly ball to be uncatchable when optical acceleration is nonzero and running speed is maximal. Chapter 3 puts this hypothesis to the test. In Chapter 4, it is examined what behaviorally relevant agent-environment factors relate to determine the affordance of catchability. Also, it is examined whether the affordance of catchability can be reliably perceived. Following up on the findings from Chapter 4, the locomotor abilities of athletes are studied in Chapter 5. Central to this chapter is the quest to chart the relationship among maximal running speed, maximal running acceleration and the total distance that can be covered over time. Various locomotor strategies and target distances will be considered in doing so. In the closing sections of Chapter 5, a conceptual model of affordance-based control in catching fly balls will be presented. Finally, Chapter 6 evaluates the merits of this conceptual model and closes off with a discussion on the future direction of research on affordance-based control.

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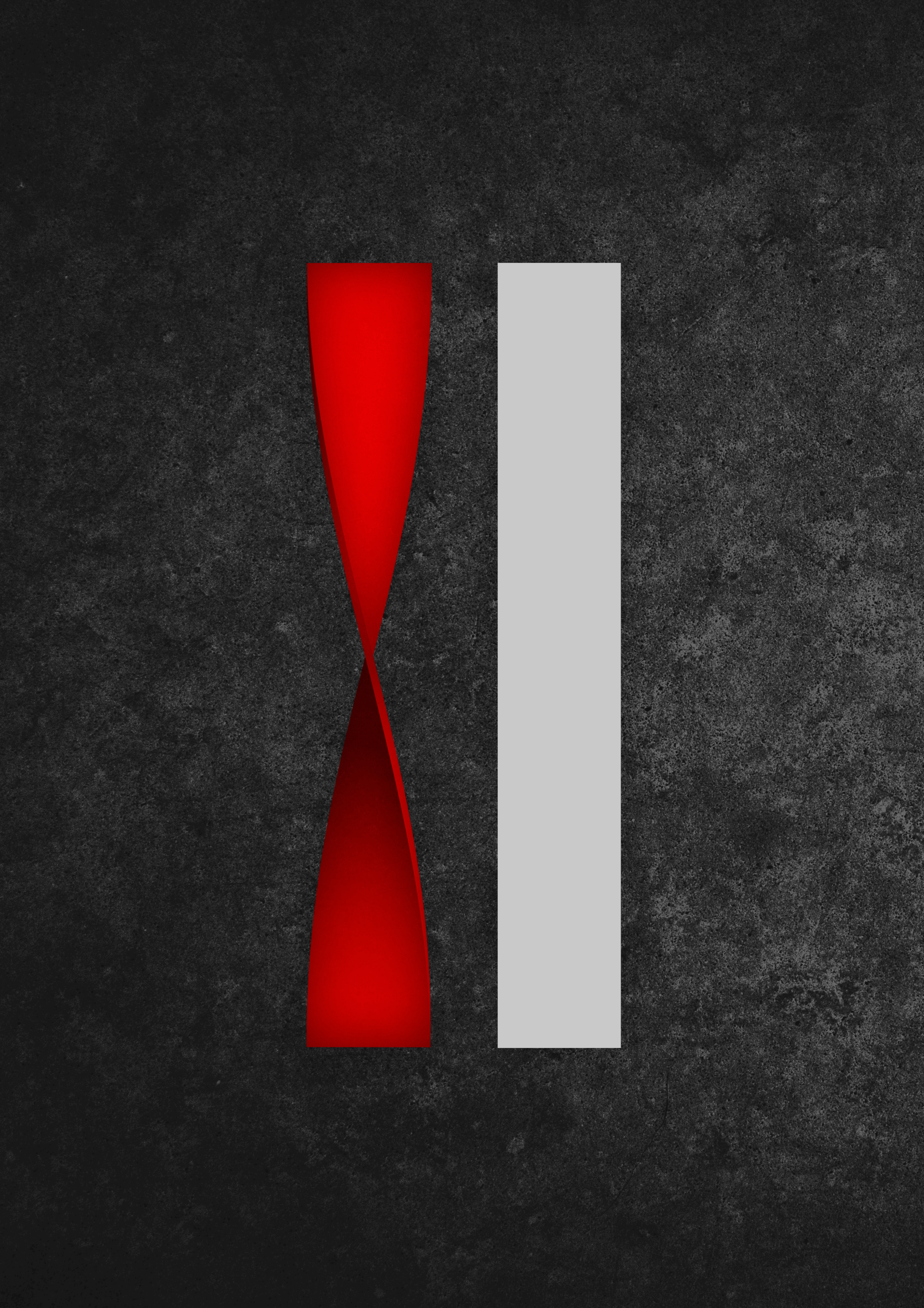

KEEPING YOUR EYES CONTINUOUSLY ON THE BALL WHILE RUNNING FOR CATCHABLE AND UNCATCHABLE FLY BALLS

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When faced with a fly ball approaching along the sagittal plane, fielders need information for the control of their running to the interception location. This information could be available in the initial part of the ball trajectory, such that the interception location can be predicted from its initial conditions. Alternatively, such predictive information is not available, and running to the interception location involves continuous visual guidance. The latter type of control would predict that fielders keep looking at the approaching ball for most of its flight, whereas the former type of control would fit with looking at the ball during the early part of the ball's flight; keeping the eyes on the ball during the remainder of its trajectory would not be necessary when the interception location can be inferred from the first part of the ball trajectory. The present contribution studied visual tracking of approaching fly balls. Participants were equipped with a mobile eye tracker. They were confronted with tennis balls approaching from about 20 m, and projected in such a way that some balls were catchable and others were not. In all situations, participants almost exclusively tracked the ball with their gaze until just before the catch or until they indicated that a ball was uncatchable. This continuous tracking of the ball, even when running close to their maximum speeds, suggests that participants employed continuous visual control rather than running to an interception location known from looking at the early part of the ball flight.

INTRODUCTION

Catching a fly ball not only adds to a good result in a baseball game but also keeps fascinating spectators and scientists alike. A particularly famous catch was the one made by Willie Mays in the 1954 World Series. He managed to catch a seemingly uncatchable ball, after looking at the ball and running to the interception location about 475 feet (145 m) from the home plate (Adair, 2002).[1] Willie Mays's catch made it to an illustration accompanying the contribution of Chodosh, Lifson, and Tabin in the 1995 volume of the journal *Science* (Chodosh, Lifson, & Tabin, 1995). These authors claimed that Willie Mays, and other adept outfielders, do not need to track the ball with their gaze because they are able to predict where and when to intercept the ball from the initial part of the ball trajectory. This will be the issue that we address in the present contribution: Does it suffice to view only the initial part of the ball's flight to predict the interception location or do fielders continuously track the ball with their gaze while running to that interception location?

Two types of strategy for the interception of moving targets have been distinguished in the literature (e.g., see Arzamarski, Harrison, Hajnal, & Michaels, 2007; Bastin, Craig, & Montagne, 2006; Ledouit, Casanova, Zaal, & Bootsma, 2013; McLeod & Dienes, 1996; Montagne, Laurent, & Durey, 1999; Zaal, Bongers, Pepping, & Bootsma, 2012). On the one hand are the *predictive* strategies. In the context of fly-ball catching, this type of strategy amounts to looking at the ball's trajectory and predicting the interception location from the initial conditions of the ball's trajectory, i.e. its initial velocity and initial angle (cf. Saxberg, 1987). It should be noted that the use of such predictive strategy depends on a priori knowledge about gravity and air resistance. Because of drag and spin, fly balls do not follow parabolic trajectories (cf. Adair, 2002; Brancazio, 1985; Zaal et al., 2012), which implies that a sophisticated internal model of ball-flight dynamics would have to be postulated.

An alternative to a predictive strategy is to use continuous visual guidance of locomotion on the basis of prospective information. Rather than having to know the interception location and time from early conditions, *prospective strategies* (e.g., see Bootsma, 2009; Bootsma, Fayt, Zaal, & Laurent, 1997; Fajen, Riley, & Turvey, 2009) involve continuously available information that can be used to know whether the current action (e.g., running speed) will lead to a successful interception. In the context of the interception of fly balls, one such model states that if a fielder keeps the ball moving on a linear optical trajectory (LOT), he or she will arrive at the interception location in time, without knowing when and where the interception will take place (McBeath, Shaffer, & Kaiser, 1995; Shaffer & Mcbeath, 2002; Shaffer, McBeath, Roy, & Krauchunas, 2003; Sugar, Beath, & Wang, 2006). The LOT strategy boils down to making sure that the horizontal and vertical components of the gaze angle (the angle between the heading and the gaze direction) change proportionally. Locomotion patterns of fielders running to catch fly balls travelling to locations in front or behind, and to the side of the fielders' initial positions have been reported to be in line with a LOT strategy (e.g., Shaffer & Mcbeath, 2002; Shaffer, McBeath, Krauchunas, & Sugar, 2008). Several authors have claimed that keeping a linear optical trajectory is not sufficient to guarantee interception because linear optical trajectories can also occur for unsuccessful interceptions (Fink, Foo, & Warren, 2009; McLeod, Reed, & Dienes, 2002, 2006; McLeod, Reed, Gilson, & Glennerster, 2008). Furthermore, for balls approaching a fielder along the sagittal plane, a LOT strategy cannot

[1] See http://en.wikipedia.org/wiki/The_Catch_(baseball)

be applied because there is only a vertical gaze angle; because there is no horizontal component of the gaze angle, all ball trajectories, leading to catches or not, will result in linear optical trajectories.

When a fly ball approaches along the sagittal plane, only running in the forward and backward direction needs to be controlled. In 1968, the physicist Neville Chapman (Chapman, 1968) considered the mathematics of the situation of a fly ball on a parabolic trajectory approaching a fielder head on. He showed that the rate of change of the tangent of the gaze angle (the angle between the line of gaze and the horizontal, assuming that the gaze is directed at the ball) would remain constant if the fielder runs to the interception location at a constant speed. Thus, for fielders to arrive at the right place in the right time, the Chapman strategy amounts to keeping this rate of change constant. Because the rate of change of the tangent of the gaze angle is equivalent to the speed of the image of the ball along an image plane, and because keeping speed constant is equivalent to keeping acceleration at zero, the Chapman strategy is also known as the Optical Acceleration Cancellation (OAC) strategy (cf. Michaels & Oudejans, 1992; Todd, 1981; see also McLeod & Dienes, 1996; Mcleod, Reed, & Dienes, 2003; McLeod et al., 2006).

Empirical studies have shown that fielders, running to catch fly balls, show locomotion patterns that are consistent with the use of the OAC strategy (McLeod & Dienes, 1996; McLeod, Reed, & Dienes, 2001; Michaels & Oudejans, 1992; Zaal & Michaels, 2003). Because the OAC strategy is a strategy based on prospective information, it predicts that locomotion paths will differ for balls that land in the same spot but with different trajectories. This has been demonstrated in catching cricket balls (McLeod & Dienes, 1996), intercepting baseballs (Fink et al., 2009), and heading virtual soccer balls (McLeod et al., 2008).
The Chapman strategy specifically applies to fly balls that approach the fielder head on. As mentioned before, the textbook (e.g., Bruce, Green, & Georgeson, 2003; Coren, Ward, & Enns, 2004) candidate complementary strategy to deal with the lateral component of running is the LOT strategy.[2] If fielders control their locomotor trajectories on a moment-to-moment basis and use prospective information, they need to rely on a constant informational coupling with the approaching fly ball. However, according to Chodosh and colleagues (Chodosh et al., 1995), there is no need for such continuous visual coupling because fielders are capable of predicting the future landing location of the ball based on rudimentary information of its trajectory: These authors argued that real fielders, like Willie Mays, simply look at the ball, predict the interception location, run there at maximal speed, and wait for the ball to arrive. Quite surprisingly, the issue of whether or not the catching of fly balls involves a constant visual coupling has not yet received much scientific attention. A notable exception is the study by Oudejans, Michaels, Bakker, and Davids (1999), which examined gaze direction of fielders confronted with approaching fly balls.

Oudejans and colleagues (Oudejans et al., 1999) were interested in the potential contribution of extraretinal systems for picking up the information to guide running to intercept fly balls (see also Bongers & Michaels, 2008). They argued that if the ball is tracked with gaze, not only

[2] Recent research, using virtual reality, has shown that the LOT strategy might not be the final answer (Fink et al., 2009; McLeod et al., 2008), and other strategies to complement the OAC strategy have been put forward (e.g., strategies of keeping constant the bearing angle—the CBA strategy, see (Chapman, 1968), or its first temporal derivative—see (McLeod et al., 2006).

the retinal system but also vestibular or proprioceptive systems might be used to pick up optical acceleration. Participants were equipped with a gaze-tracking system, and were allowed to make a few steps in the right direction for fly balls projected at them head on. Because the gaze tracker was connected with a cable to the recording unit, fielders could only move about one or two steps forward or backward. Interesting in the present context is the finding that participants in the Oudejans et al. study, indeed, kept their eyes on the ball, by moving both their heads and eyes.

When using a predictive strategy, fielders obviously need to look at the ball during the initial part of its flight. Certainly, there is no need to keep the eyes on the ball during its entire flight. Although the use of a prospective strategy does not necessitate such continuous tracking of the ball (intermittent looking at the ball would suffice), the finding that fielders do continuously track the ball would fit the use of a prospective strategy better than it would the use of a predictive strategy. The present paper reports an experiment in which we tracked the gaze of participants in a setting in which approaching fly balls either were within their locomotor reach (i.e., balls were catchable) or were not within their locomotor reach (i.e., balls were uncatchable). Importantly, the gaze tracker that we used was mobile, and allowed the participants to utilize their natural range of motion. That is to say, whereas Oudejans et al. (1999) have shown that their participants continuously tracked the balls with their gaze for balls falling at or near the initial position of the fielder or when simply watching balls that landed farther away than two steps, the present study allows to establish this behavior while fielders are free to run much greater distances, even reaching their top speeds. Furthermore, we studied two situations. In line with the majority of previous studies on catching fly balls, we considered balls that would fly close enough to the participants that they would be able to make it to the interception location in time. In addition, we also studied the situation in which balls were projected so far away from the participants' starting position that they would not be able to reach the ball before it would hit the floor. We had participants indicate when they knew that a ball would be uncatchable, and when this occurred we inspected the direction of gaze up until this point. In short, the present study considered running to catch fly balls under the demanding circumstances as seen in regular ball games. Tracking the ball might be regarded much more difficult when running close to full speed. When even under these strenuous conditions we would find pursuit tracking of the ball, we argue, this gaze behavior must have a functional origin, which most probably would be related with continuous visual control.

METHODS

Participants

Ten female volunteers (mean age 21.7 ± 2.2 years) participated in the experiment. To be included, they needed to have at least two years of experience in ball sports. All participants reported normal, or corrected to normal (lenses) vision. Prior to the experiment, participants were informed about the procedure of the study and gave their written informed consent. The study was approved by the Ethics Board of the Center for Human Movement Sciences (University Medical Center Groningen, the Netherlands), and the protocol was in accordance with the Declaration of Helsinki.

Apparatus

To determine the point of gaze (PoG), participants were equipped with a monocular, mobile eye tracker (Mobile Eye, Applied Science Laboratories, Bedford, MA). The tracking system consists of a scene camera (recording the field of view of the participant), and an optics module that consists of a near infrared light source and an eye camera. All components are mounted on a pair of lightweight spectacles. Calculation of the point of gaze is based on 'dark pupil tracking' and involves detection of the center of the pupil and the reflection of a cluster of three infrared LEDs on the cornea. Eye rotations are calculated from the angle and length of the vector connecting the pupil center and the corneal reflection. After calibration (see below), eye rotations are mapped onto the scene view, establishing the PoG in the scene. Interleaved images of the eye camera and the scene camera were recorded on tape using a portable video recorder (Sony GV-D1000E DVCR), at 30Hz. The PoG was represented in the scene view by a crosshair with an approximate accuracy of 1° visual angle. The visual range of the eye tracker is 50 degrees horizontally, and 40 degrees vertically. The weight of the system, excluding the video recorder, is 76 grams. During testing, the video recorder was worn in a pouch around the waist, and allowed near-normal mobility for the participant.

The eye tracker was calibrated using a 3.3 m high by 4.4 m wide grid with 20 equally spaced points (4 rows of 5 dots each), representing a visual angle of 16.9° in the horizontal and 12.6° in the vertical direction. During calibration, the participants were positioned 15 meters from the grid, while their head rested on a chinrest that fixated the head. The gaze tracker was calibrated prior to the start of the experiment, after each set of 18 trials, and also when the participant indicated that the tracker had changed its position on the head during testing.

Setup and procedure

The experiment was performed in a well-lit gymnasium (50 x 30 x 10 m). A ball-projecting machine (Louisville Slugger, type UPM45 Blue Flame) with adjustable force and projection angle was used to deliver tennis balls along the sagittal plane of the participant, at different projection distances. Since the projection angle could be manipulated only within a limited range, we used wooden blocks that were placed underneath the ball projection machine to generate the desired trajectories. The projected distance of the fly balls was varied systematically by adjusting the projection force and angle, and ranged approximately from 10 to 29 m. The apex of the trajectory was about 8.5 m for every trial, so that all fly balls had an approximate flight time of 2.5 s. The ball-projecting machine was occluded from sight to prevent visual anticipation of the ball's trajectory.

Participants completed 54 trials. The initial position of the participant was 20 m from ball projection, and was identical in all trials. At the start of each trial, the experimenter verbally cued the participant before ball delivery. Participants were instructed not to make a dive to perform a successful catch. Other than that, participants were free to move as they felt necessary to catch the ball. No instructions were given with regard to catching strategies (e.g. overhand or underhand catching). Not all projected balls were catchable. Participants were instructed to call 'no' at the instant they realized that they were unable to catch the ball.

Data analysis

We used EyeVision software (Applied Science Laboratories, Bedford, MA) to convert the video data that were stored on tape into AVI files. We analyzed the data from the moment of ball projection until the moment the ball was either intercepted or until the moment that the participant indicated that the ball was uncatchable by calling ‘no’. We used the audio signal from the internal microphone of the eye tracking system to detect these moments. More specifically, we marked the first video frame in which the sound of ball projection was audible as the first video frame for further analysis. The final frame that was analyzed for each trial corresponded either with the first frame in which the sound of the ball hitting the hand of the fielder was audible, or the first frame in which the sound of the participant calling ‘no’ was audible. Audio analysis of the video data was performed in Adobe Premiere CS6.

To assess whether gaze tracked the ball, we considered the distance between the point of gaze (PoG) and the ball image, for each video frame. We used the EyeVision software to establish the 2D position of the PoG in the scene plane. Next, we used ASL Results Plus GM software (Applied Science Laboratories, Bedford, MA) to filter invalid values for the PoG. With custom-made software in MATLAB (Mathworks R2012b), we determined the 2D position of the ball in the scene plane, by hand. Finally, we computed the absolute distance in pixels between the PoG and the ball in the scene image.

We assigned points of gaze to one of two categories: Either on the ball (‘tracking’) or not on the ball (‘other’). The PoG was considered to be on the ball whenever the absolute distance in the scene plane was smaller than 75 pixels (corresponding to 6.25° visual angle). Although theoretically this criterion allows for changes in distance of 150 pixels between successive frames to be assigned to the ‘tracking’ category, it turned out that these changes were smaller than 25 pixels in 95.8% of the frames identified as ‘tracking’, and that in only 0.4% of the ‘tracking’ frames the change was greater than 75 pixels.

For each trial, the relative contributions of frames associated with ‘tracking’ and ‘other’ behavior will be expressed as a percentage of the total number of frames that had valid a PoG. Furthermore, we will present median distances between the PoG and the ball, as well as interquartile ranges.

RESULTS

The relation between the PoG and the ball could be established in 74.7% of all video frames. In the remaining frames, the relation between the ball and the PoG could not be assessed, either because the ball could not be identified in the video frame or because the PoG was lost. Unsuccessful calibration of the Mobile Eye led us to exclude the data from two participants from further analysis. Finally, 20 trials were excluded from further analysis because participants did not catch the ball but also did not indicate that it would be uncatchable (16 trials) or because we were unable to determine whether participants had touched the ball (4 trials).

Preliminary video analysis suggested that participants almost exclusively directed their point of gaze to the ball and rarely directed their gaze to locations elsewhere in the scene. The average median distance between the PoG and the ball was 24.26 pixels (with an average interquartile range of 22.67 pixels); medians (interquartile ranges) were 23.10 (20.28) pixels in the trials in which balls were caught (n = 230), and 25.85 (25.58) pixels in the trials in which balls were judged to be uncatchable (n = 168). Participants tracked the ball, on average, in 95.5% of the trial when they caught the ball, and in 92.9% of the trial when they called a ‘no’.

As detailed in the Methods section, video frames in which the distance between the ball and the PoG was more than 75 pixels formed the ‘other’ category. Further investigation of this category (representing 5.7% of all frames with a valid PoG) showed that 3.1% of all ‘other’ gaze behavior constituted meaningful gaze behavior and could be classified as ‘fixations’ (operationally defined as stable gaze for three or more consecutive frames). That is, fixations on items other than the ball accounted for 0.2% of all displayed gaze behavior.

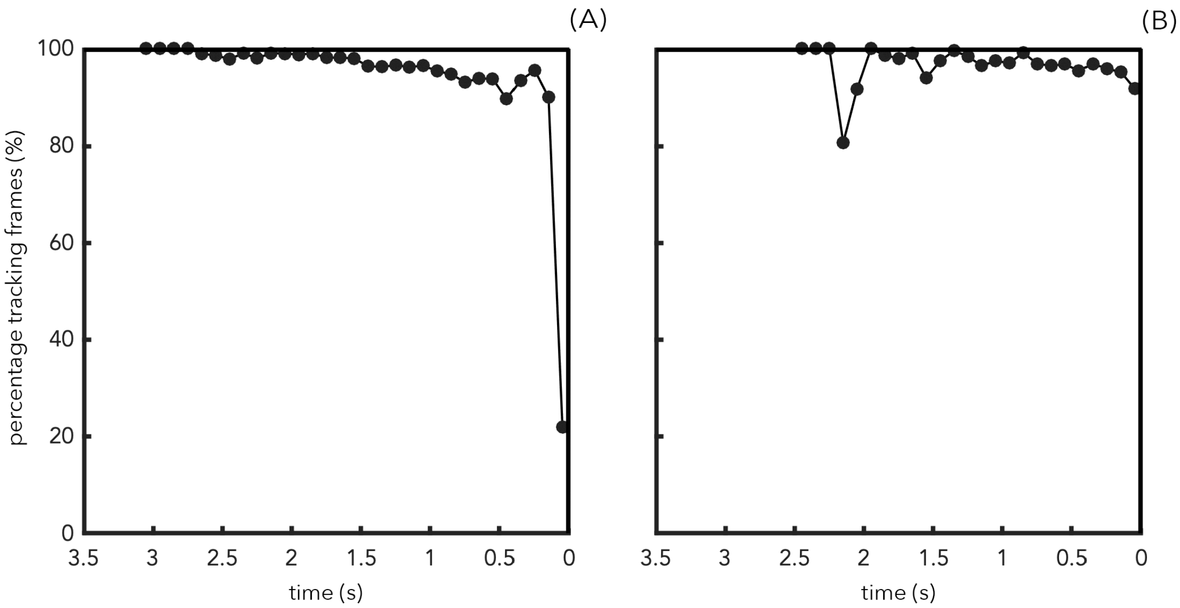

Figure 1. Percentage of tracking as a function of time. The number of frames in which participants tracked the ball expressed as a percentage of the total number of frames with valid data in a trial. A) Average percentages for trials in which the ball was caught; $t = 0$ represents the time of contact with the ball; B) Average percentages for trials in which the ball was judged to be uncatchable; $t = 0$ represents the time that a ‘no’ was called.

Figure 1 gives the percentage of frames that were categorized as ‘tracking’ as a function of time. Data points are represented in bins of 100ms, combining sets of three consecutive video frames. In Figure 1A, which shows the trials in which the balls were caught, the abscissa represents the time until contact with the ball. It can be seen in Figure 1A that the contributions of tracking behavior to total gaze behavior remained relatively constant throughout the trial. Only the last 100ms before the catch deviated substantially from this trend. Figure 1B represents the trials in which participants judged balls to be uncatchable. In Figure 1B, the abscissa represents the time until the moment a ‘no’ was called. Also for this type of trials, the contribution of tracking behavior to total gaze behavior remained relatively constant throughout the trial. A slight deviation from this trend can be seen in the left side of Figure 1B (i.e., the two bins spanning from $t = 2.2$ to $t = 2.0$). Because these early bins included only few trials, the percentages of these bins were sensitive to the presence of single frames with a PoG that was coded as “other”. More particularly, one trial that had a few consecutive frames that were classified as ‘other’ early on in the trial (more than 2 s before the participant called ‘no’) was mostly responsible for the apparent decrease in tracking behavior.

DISCUSSION

In his famous catch in 1954, Willie Mays looked at the ball, turned his back to the ball while running, and finally looked back at the ball again. Is this the usual way for fielders running to catch a fly ball? Do they simply know where to run from a single glance on the ball's trajectory (cf. Adair, 2002; Brancazio, 1985; Chodosh et al., 1995; Saxberg, 1987), or do fielders need continuous monitoring of the ball's position? The results of the present study show that fielders running to catch an approaching fly ball continuously keep their eye on the ball. Although the use of a predictive strategy would not preclude continuous tracking of the ball, and the use of a prospective strategy would not necessitate 100% tracking, the gaze behavior of our participants suggests that their running is under continuous visual control, characteristic for a prospective strategy.

Earlier work by Oudejans et al. (1999) showed that their participants reliably tracked the ball in both a fly-ball watching and a catching task. In the majority of trials administered by Oudejans and colleagues, participants were asked to simply observe fly balls approaching head on. Watching these balls resulted in pursuit tracking, with both head and eye movement contributing to keeping the gaze on the ball. In a catching condition, participants were allowed to move and actually catch the approaching balls. Because the gaze tracker used by Oudejans et al. was wired, it restricted the participants' mobility, such that they were only able to make a few steps to intercept a fly ball. As a consequence, balls in their catching condition had to be projected within a few meters from the participants' initial position. Also in the catching condition, participants tracked the ball with their gaze, although the contributions of head and eye movement to directing the gaze were different than in the watching conditions (see also Zaal & Michaels, 2003). The present study allowed fielders to move as they would naturally do when catching a fly ball. With the mobile gaze tracker that we used, we were able to study gaze in situations comparable to real catching in the outfield.

Participants in the present study tracked the ball with their gaze nearly exclusively, regardless of the projected distance. Furthermore, they also showed tracking of balls that they realized were uncatchable. This latter condition is not commonly part of a study into the control of interception, although it is part and parcel of the reality of outfielders. The results suggest that the information for knowing that a ball cannot be caught should not be sought in a failure to keep tracking a ball. That is to say, our participants tracked the ball up until the moment that they indicated that the ball was out of their reach. They had no problems doing so, even when running at their maximum speed. Clearly, a failure to track the ball was no indication for the participants that an approaching ball would be uncatchable.

As discussed before, our results demonstrate that participants track the ball throughout its trajectory. We would like to stress that especially the fact that tracking continues to just before the actual catch speaks in favor of the use of continuous guidance rather than early prediction. Both the use of a predictive and of a prospective strategy would predict gaze pursuit during the early part of ball flight. However, when using a predictive strategy, in which the interception location and time are inferred from the first part of the ball trajectory, there seems to be no advantage of keeping an eye on the ball for the rest of its flight; continuous tracking fits more naturally with continuous visual control. Only during the very final part of the ball's approach, approximately during the final 100ms, did tracking become inconsistent. A reason for this might be that the fielders had actually stopped tracking the ball with their gaze because it was not needed for arriving at the interception location anymore. It has been suggested that fly ball interception consists of two phases; locomotion to the interception point and making the actual catch (e.g., see Fink et al., 2009; Michaels & Oudejans, 1992). The last 100ms might reflect the latter phase. Alternatively, participants might have started to prepare for a follow-up action, such as throwing the ball to a teammate.

In conclusion, the present results paint a picture that is highly consistent with the use of a prospective strategy in dealing with the outfielder problem. Gaze data are not able to show indisputably that fielders do not use a predictive strategy, in which they know where to run from looking at the early part of ball flight. However, the finding that fielders continuously keep their eye on the ball, while running several meters to catch a ball that might or might not be catchable, fits naturally with a continuous visual control on the basis of prospective information.

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WHEN A FLY BALL IS OUT OF REACH: CATCHABILITY JUDGMENTS ARE NOT BASED ON OPTICAL ACCELERATION CANCELLATION

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The optical acceleration cancellation (OAC) strategy, based on Chapman's (1968) analysis of the outfielder problem, has been the dominant account for the control of running to intercept fly balls approaching head on. According to the OAC strategy, outfielders will arrive at the interception location just in time to catch the ball when they keep optical acceleration zero. However, the affordance aspect of this task, that is, whether or not an approaching fly ball is *catchable*, is not part of this account. The present contribution examines whether the scope of the OAC strategy can be extended to also include the affordance aspect of running to catch a fly ball. This is done by considering a fielder's action boundaries (i.e., maximum running velocity and –acceleration) in the context of the OAC strategy. From this, only when running velocity is maximal and optical acceleration is non-zero, a fielder would use OAC to perceive a fly ball as uncatchable. The present contribution puts this hypothesis to the test. Participants were required to try to intercept fly balls projected along their sagittal plane. Some fly balls were catchable whereas others were not. Participants were required to catch as many fly balls as possible and to call 'no' when they perceived a fly ball to be uncatchable. Participants' running velocity and –acceleration at the moment of calling 'no' were examined. Results showed that participants' running velocity was submaximal before or while calling 'no'. Also running acceleration was often submaximal. These results cannot be explained by the use of OAC in judging catchability and ultimately call for a new strategy of locomotor control in running to catch a fly ball.

INTRODUCTION

Making a catch in baseball is arguably one of the most spectacular ways to gain advantage on the batting team. Whenever a catch is made, the batter is out and the runners have to tag-up (i.e. touch their time-of-pitch base), providing the fielding team with a unique strategic advantage. Running to intercept a fly ball can be a demanding task in which careful locomotor control is required to get to the right place in the right time to make the catch. A large number of studies have addressed the locomotor control involved in catching fly balls. The strategy most widely accepted to account for the control of running to catch fly balls that approach head on is *the Chapman strategy* (Chapman, 1968; Fink et al., 2009; McBeath et al., 1995; McLeod et al., 2002, 2006; McLeod et al., 2008; Shaffer & McBeath, 2002; Shaffer et al., 2008; Shaffer et al., 2003). Paradoxically, a hardly addressed issue in this account of catching fly balls is that of perceived catchability. Some fly balls are catchable whereas others are not. Catchability depends on the action boundaries of a fielder (e.g. maximum running velocity and –acceleration) as well as on the flight characteristics of a ball (e.g. flight time and –distance). That is to say, when the ball flight allows enough time for a fielder to cover the distance to the interception location, the ball would be catchable. If, however, the fielders running capabilities make that more time is needed to run to that same location, this would yield the ball uncatchable. Presumably, this affordance of catchability plays a role in running to catch a fly ball (Fajen, 2007). For example, if a fly ball is perceived uncatchable, a fielder's primary goal might no longer be to make the catch, but to get the ball after the first bounce. The latter situation requires different timing and coordination, illustrating that perceived catchability could have a profound effect on the way locomotion is controlled. In addition, it might well be the case that fielders will speed up when their current running speed only just suffices to reach the interception location (just as shown to be the case in engaging the brake in driving; see Fajen, 2005a). In this study, we will examine whether the scope of the Chapman strategy, the dominant account for the timing of running to catch fly balls, can be extended to also include the affordance aspects of this task (i.e. perceived catchability). This will be a first step towards developing an affordance-based control account (Fajen, 2007) for catching fly balls.

In 1968, Neville Chapman considered the dynamics of running to catch a fly ball (Chapman, 1968). Although Chapman did consider the forward-backward as well as the lateral component of running to catch fly balls, the former has received the most attention, probably because this component in his analysis determines the timing of interception. For a ball approaching an outfielder head on, he showed that the rate of change of the tangent of the elevation angle α of the ball (i.e. $d(\tan\alpha)/dt$) is constant for the constant running velocity that would lead a fielder to the right place in the right time to intercept a fly ball. Deviations from a constant value of $d(\tan\alpha)/dt$ can be corrected for by adjusting locomotor velocity. An increase in $d(\tan\alpha)/dt$ specifies that a fielder's current locomotor velocity is such that the ball will fly overhead, whereas a decrease in $d(\tan\alpha)/dt$ specifies that the fielder's locomotor velocity is insufficient to reach the landing location in time. Adjusting locomotor velocity such that $d(\tan\alpha)/dt$ remains constant has become known as the Chapman strategy (e.g., Chapman, 1968; Dienes & McLeod, 1993; Kistemaker et al., 2008; McLeod & Dienes, 1996; Michaels & Oudejans, 1992; Michaels & Zaal, 2002; Zaal & Michaels, 2003).

For an outfielder to take advantage of the Chapman strategy, information related to $d(tan\,\alpha)/dt$ must be optically available. That is to say, a fielder must be able to perceive whether his or her current locomotor efforts are sufficient for keeping constant $d(tan\,\alpha)/dt$. When fielders track the ball with their gaze (see Oudejans et al., 1999; Postma et al., 2014), the elevation angle α equals the gaze angle. In this case, gaze angle can be the basis for using the Chapman strategy. A more general solution, also useful when gaze is not directed at the ball, can be found in the optical array (cf. Michaels & Oudejans, 1992; Todd, 1981). From a fielder's point of view, the optical position of the ball—the projection of the ball on a planar projection plane—will rise at constant speed if $d(tan\,\alpha)/dt$ is constant. Thus, in essence, the Chapman strategy amounts to keeping optical velocity constant. Since keeping optical velocity constant is equivalent to nulling optical acceleration, the Chapman strategy is also known as the Optical Acceleration Cancellation (OAC) strategy. If optical velocity is not constant (i.e. optical acceleration ≠ 0), $d(tan\,\alpha)/dt$ is not constant either and the fielder must make locomotor adjustments to make it in time to make the catch. For reasons of consistency, we will only use the term OAC strategy from here on out.

Empirical studies have shown that fielders' locomotor patterns are consistent with the OAC strategy. For successful interception, fielders have been shown to run in such a way that optical acceleration equals zero for the largest part of their running movement (Dienes & McLeod, 1993; McLeod & Dienes, 1996; Michaels & Oudejans, 1992). Fink and colleagues (2009) consolidated this finding by showing that locomotor patterns were not merely coincidental to naturalistic interception of fly balls, but actually resulted from online visual control of optical acceleration. To test this, Fink and colleagues had participants intercept baseballs in virtual reality. This allowed the experimenters to perturb the trajectory of a ball mid-flight. Results showed that participants corrected for optical acceleration, resulting from perturbations to the ball trajectory, in order to make the catch. Not only locomotor behavior appears to be in line with the OAC strategy, also gaze behavior fits the use of optical acceleration. It has been shown that participants maintain continuous visual contact with the ball while running to make a catch, even for balls that fly overhead. (Oudejans et al., 1999; Postma et al., 2014). Such gaze behavior fits naturally with the use of the OAC strategy, as it implies continuous visual control of interception.

The OAC strategy is in essence an error-nulling strategy (Fajen, 2005a; 2005b; 2005c; 2007; McBeath et al., 1995). Nulling optical acceleration, by adjusting locomotor velocity, will lead a fielder to the right place in the right time to make a catch. However, nulling optical acceleration is a condition that is not always possible to satisfy. The change in optical acceleration that a fielder can bring about by adjusting running velocity and/or -acceleration is limited by the locomotor abilities of the fielder. That is to say, locomotor constraints on part of the fielder, determine whether optical acceleration can be nulled. This is the problem of action boundaries (Fajen 2005a; 2005b; 2005c; 2007). Action boundaries constrain what one can and cannot do: some fly balls are catchable while others are not. Fajen (2005a; 2005b; 2005c) argued that people are aware of their action boundaries and that they act accordingly to control behavior. As such, behavioral control strategies should not only be about sufficiency but also about possibility. What lies within the action boundaries of an actor to attain a certain goal? Or analogously: What is afforded given the action boundaries of the actor? Based on this notion, Fajen (2005a; 2005b; 2005c; 2007) developed the concept of *affordance-based control*: A novel conceptualization of motor control in which affordances, or action possibilities, rather than error-nulling principles are cardinal to understanding behavior (for an excellent review on affordance-based control, please refer to Fajen 2007.)

In the present contribution, we examined whether the OAC strategy can be made compatible with the concept of affordance-based control. While the OAC strategy is an error-nulling strategy and action boundaries have no part in its original formulation, optical acceleration might still be used in perceiving the affordance for catchability. From the OAC strategy, catchability can be observed under two specific conditions. First, if optical acceleration equals zero, and assuming that a fielder's current locomotor velocity can be maintained, the fielder knows that a fly ball will be *catchable*. Second, a fielder knows that a fly ball will be *uncatchable* when optical acceleration does not equal zero but locomotor velocity cannot be further increased (either forwards or backwards) to cancel out optical acceleration. In this case, the locomotor qualities of the fielder serve as a constraint on optical acceleration cancellation, informing the fielder of (un)catchability. Thus, from the OAC strategy, catchability can be directly perceived from either one of these aforementioned conditions.

However, when optical acceleration does not equal zero *and* the fielder is not running at maximum speed, optical acceleration cannot inform about catchability. To appreciate why this is the case, it is important to understand that there is no one-to-one relationship between optical acceleration and the locomotor adjustment required to null the error. This stems from the fact that optical acceleration is determined by optical position, which is a function of the position of the fielder relative to the ball. Optical position follows one-to-one from a specific fielder-ball geometry. Yet, the reverse is not true: no specific fielder-ball geometry follows from optical position. To illustrate this, consider a fly ball approaching a fielder head on. At some point in time, the fly ball is positioned both one meter above eye-level and one meter in front of the fielder. From this specific fielder-ball geometry, it can be derived that the angle at which the ball approaches the fielder is 45 degrees. Yet, solely from optical position (in this case 45 degrees), it cannot be derived that the ball is one meter in front of the fielder and one meter above eye-level. The ball might as well be ten meters up and ten meters away (given that the optical size of the ball has no part in the OAC strategy). As such, optical position holds no information about distance, and hence there are an infinite number of ball positions that give rise to the same optical position. Consequently and analogously, the magnitude of optical acceleration holds no information about the required locomotor adjustment or whether this adjustment is within the action boundaries of the fielder. Ergo, the affordance of catchability cannot be directly perceived when the fielder is not running maximally *and* optical acceleration is non-zero. From the OAC strategy, catchability can thus only be perceived under specific circumstances.

In this study, we examined whether judgments of perceived catchability would fit the use of the OAC strategy. To test this, we designed an experiment in which participants were required to intercept tennis balls projected along their sagittal plane. Some balls were projected within the locomotor range of the participant (these were potentially catchable), whereas others were projected beyond the locomotor range of the participant (these were uncatchable). Participants were required to intercept as many fly balls as possible and were instructed to call 'no' whenever they felt that a fly ball would be uncatchable. The kinematic profiles for trials in which a participant called 'no' were studied to establish whether judgments of catchability could have been based on having reached maximum running velocity and/or maximum running acceleration, as would be expected from the OAC strategy.

METHODS

Participants

Two women and four men, aged (20 to 27) volunteered to take part in the experiment. All participants had considerable experience in ball sports (at least 11 years), yet none of them had experience with baseball per se. All participants reported normal or corrected to normal vision. Prior to the experiment all participants were informed about the procedure and gave their written informed consent. The experiment was approved by the Ethics Board of the Center for Human Movement Sciences (University Medical Center Groningen, the Netherlands), and the protocol was in accordance with the Declaration of Helsinki.

Design

Participants were required to intercept tennis balls projected at them along their sagittal plane. Tennis balls were projected either in front of- (front-trials) or behind the initial position of the participant (back-trials). Some fly balls were catchable (i.e. within the locomotor range of the participant) whereas others were uncatchable (i.e. beyond the locomotor range of the participant). Catchability was manipulated by systematically varying both flight time (1.64-3.00 seconds) and projection distance (10-20 meters for front-trials and 20-30 meters for back-trials), resulting in 24 ball trajectories (see below). We aimed at delivering an equal number of front- and back trials, and to have these sets equivalent in terms of flight time and passing distance (i.e. the distance between the initial position of the participant and the landing location of the ball). The initial position of the participant (20 meters from the site of ball projection) was the same for all trials. Participants received a total of 96 trials, which were block-randomized over 4 blocks of 24 trials. Participants were encouraged to intercept as many fly balls as possible and were instructed to call 'no' at the moment that they realized a fly ball to be uncatchable. No specific instructions were given with regard to catching strategies (i.e. underhand- or overhand catching). At the start of each trial, the experimenter verbally cued the participant for ball delivery.

Setup and apparatus

The experiment was performed in a large gymnasium (50×30×10m). Tennis balls were delivered using a pitching machine with adjustable pitch and power (Louisville Slugger, type UPM45 Blue Flame). To realize a range of projection angles beyond the factory settings of the pitching machine, it was mounted on a wooden board that could be placed at a particular angle using wooden blocks of different heights. The height of the blocks was such that the machine could be tilted 10 to 40 degrees. We used 24 sets of pitch, power, and angle combinations in the experiment. Due to slight inherent variability of the apparatus, ball trajectories at identical apparatus settings were never exactly the same. As such, the projection distance could be manipulated with an approximate accuracy of 0.5 meter. To prevent visual anticipation of the ball trajectory, the pitching machine was occluded from sight using a screen.

The experiment was recorded using an HD-camera (Canon HF100) positioned perpendicular to the plane of ball projection. The camera was set to its minimal focal length and a ×0.45 wide-angle converter was used to further increase the visual angle (122°). The camera was mounted on a tripod and a fast shutter speed (1/200) was used to prevent motion blur. The experiment was recorded at a frame rate of 25 frames per second.

Data analysis

Data from the HD-camera was imported and converted to *.MOV files using QuickTime Player (v. 10.3). Video-files were trimmed down to individual trials. The first frame associated with ball projection constituted the start of a trial. The end of a trial was dependent on its outcome (i.e. success or failure). Trials in which the participant managed to catch or touch the ball (i.e. success) were digitized up until the moment of first contact, whereas trials in which the participant failed to catch, or even touch, the ball (i.e. failure) were digitized up until the moment the ball hit the floor. Finally, Audacity (v. 1.2.6) was used to determine if and when a participant called ‘no’.

The planar coordinates of the ball and the participant’s head were digitized on a frame-to-frame basis (NBody, v.09-13; E. Otten). Using a planar checkerboard pattern, lens distortion was calculated and corrected for. The position of the ball was retrieved by identifying differences between subsequent frames through subtraction of RGB-values on pixel-level. Differences between frames were highlighted after all the frames of a trial were analyzed. From these highlighted regions, the trajectory of the ball was manually specified. The head position of the participant was digitized using a custom-made shape recognition algorithm. Whenever the position of the participant’s head could not be established automatically the position of the participant’s head was digitized manually. The digital coordinates of both the ball and the participant were transformed to real world metrics using a quaternion. The site of ball projection constituted the origin of the quaternion with the x-axis extending towards the participant and the y-axis extending towards the ceiling. The data were filtered and smoothed for final analysis. A fourth order polynomial function was used to account for missing values in the ball data; a cubic spline was used to interpolate and filter the participant data (smoothing parameter: 0.995).

To assess the running velocity and –acceleration at the moment of calling ‘no’, kinematic profiles were calculated by differentiating the participant’s positional data. Subsequently, kinematic profiles were transformed such that positive values constituted motion in the direction required to make a catch. This allowed for direct comparison of running characteristics of front-trials and back-trials. Additionally, running velocity and –acceleration at the time of calling ‘no’ were expressed as a percentage of participants’ maximum running velocity and –acceleration. For each participant, maximum running velocity and –acceleration were operationally defined as the highest values for running velocity and –acceleration over all trials for that participant (corrected for passing side). Finally, all values were summarized using probability density plots.

RESULTS

Out of a total of 576 trials, 27 trials were excluded because the ball hit the ceiling. Furthermore, 36 trials could not be digitized due to technical difficulties (e.g. irregularities in the background causing erratic tracking behavior). From the remainder of trials, only those in which a participant called ‘no’ were selected for further analysis (n=218). For these trials, the position of the ball could be established in 68.7% of all frames, while the position of the participant could be established in 98.4% of all frames. Missing values were accounted for as detailed above: for the ball data a fourth order polynomial spline was used whereas a cubic spline was used for the participant data. No participants were excluded from further analysis.

On average, participants caught 50.2% (SD = 9.7%) of the balls projected at them. Conversely, on average, participants judged 39.8% (SD = 12.9%) of the fly balls projected at them to be uncatchable. On a small number of trials (M = 5.4%, SD = 3.7%) participants failed to intercept the ball while not calling 'no' either. In the remainder of the trials, the ball hit the ceiling (as detailed above). It should be noted that participants never called 'no' for fly balls that were eventually caught.

The temporal pattern of calling 'no' (t_{no}) followed a bell-shaped distribution (figure 1a). Participants never took less than 0.8 seconds to indicate that a fly ball was uncatchable. On average, it took participants 1.42s (*SD* = 0.40s) to indicate that a fly ball was judged to be uncatchable. An independent-samples *t*-test showed that there was no significant difference ($t_{(216)}$ = -0.70, *p* = 0.482, d_s = -0.97) in absolute timing of calling 'no' for front-trials (*M* = 1.41s, *SD* = 0.45s) as compared to back-trials (*M* = 1.45s, *SD* = 0.36s). In contrast, a significant effect was apparent ($t_{(216)}$ = 4.27, *p* < 0.001, d_s = 0.59) when the timing of calling 'no' (*t=no*) was expressed as a percentage of total flight time (figure 1b). Participants judged fly balls to be uncatchable earlier in ball flight for back-trials (*M* = 55.5%; *SD* = 14.1%) as compared to front-trials (*M* = 63.8%; *SD* = 13.9%).

To assess the usefulness of optical acceleration in terms of catchability, we will turn to the kinematics of the participants. As discussed before, taking the OAC strategy as framework, catchability can be judged under one of two specific circumstances: either optical acceleration equals zero, indicating that a ball is catchable, or optical acceleration does not equal zero *and* the participant is running at his or her maximum velocity, indicating that a fly ball is uncatchable. To test whether perceived catchability fits the OAC strategy, we analyzed participants' running velocity (and –acceleration) at the time of calling 'no' (t_{no}). The results show that participants never ran at their maximum velocity at t_{no} (figure 1c). In fact, on occasions, participants were even standing still while calling 'no'. On average, participants ran at 46.4% (*SD* = 7.9%) of their maximum speed when calling 'no'. An independent-samples *t*-test showed that participants exhibited a significantly ($t_{(216)}$ = -2.14, *p* = 0.034, d_s = -0.30) lower relative running speed while calling 'no' in front-trials (*M* = 43.3%; *SD* = 19.1%) as compared to back-trials (*M* = 49.4%; *SD* = 21.8%), see also figure 1c. Interestingly, for back-trials, participants occasionally called 'no' while running in the wrong direction (i.e. towards the site of ball projection), as can be seen from the small negative peak in figure 1c.

Rather than maximum running velocity, participants might also have used maximum acceleration in making perceptual judgments of catchability. However, the results show that participants also never accelerated maximally at t_{no}. Participants were on average decelerating at the moment of calling 'no' in front-trials (*M* = -4.7%; *SD* = 18.1%), whereas participants were on average accelerating in back-trials (*M* = 4.94%; *SD* = 19.2%). Using an independent-samples *t*-test, this difference was found to be significant ($t_{(216)}$ = -3.50, *p* < 0.001, d_s = -0.48), see also figure 1d (It is important to note that the kinematic profiles were transformed such that a positive value for either velocity or acceleration constitutes motion in the required direction).

Finally, we examined the peak locomotor values (i.e. maximum velocity and –acceleration) reached by participants before calling 'no'. On average, participants reached a peak velocity of 54.0% of their maximum running velocity (*SD* = 19.1%) and a peak acceleration of 71.2% of their maximum running acceleration (*SD* = 15.6%) before calling 'no'. Participants rarely reached peak locomotor values greater than 90% of their maximum running velocity (*n* = 2) or –acceleration (*n* = 19), before calling 'no' (see also supplementary figure 1). These trials made out only 0.9% and 8.7% respectively of all trials in which a participant called 'no'.

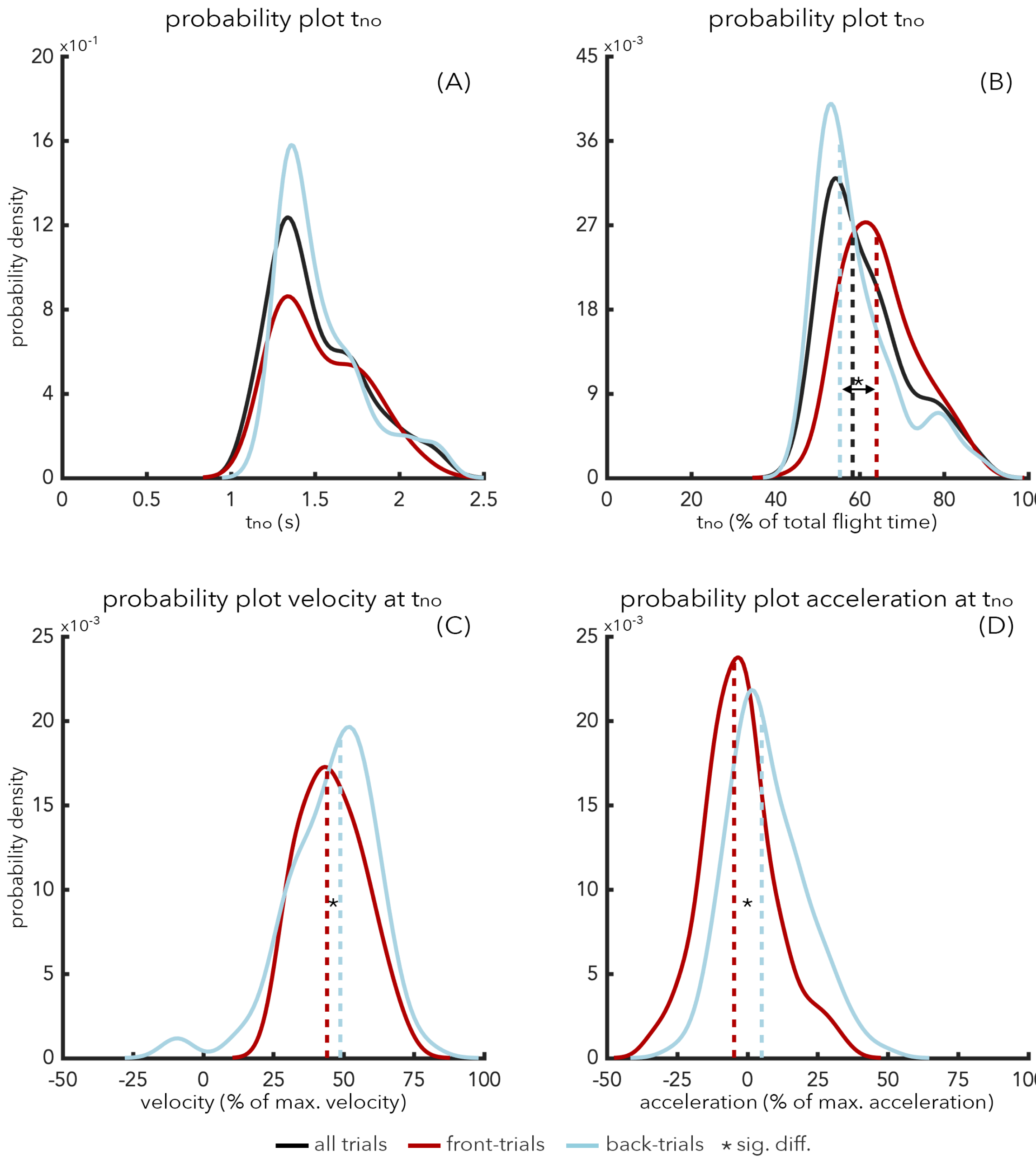

Figure 1 (A), (B), (C), (D). Probability density plots showing the relative likelihood of relevant temporal-spatial characteristics in indicating that a fly ball is perceived to be uncatchable. The abscissa represents the range of relevant values associated with the variable in question. The ordinate represents probability density values. The integral of a specific range provides the cumulative probability of value *x* of property *y* falling within that range. The integral of a probability density function is always equal to 1. Probability functions (solid lines) are presented along with a graphical representation of the mean (dashed lines) for front-trials (red lines), back-trials (blue lines) and, if applicable, all trials (black lines). Panel A represents the probability density function for the absolute timing of calling 'no' from trial onset. Panel B represents the probability density function for the relative timing of calling 'no'; i.e. expressed as a percentage of the total duration of a trial. Panel C represents the probability density function for the running velocity when calling 'no', expressed as a percentage of maximum velocity. Finally, panel D represents the probability density function for running acceleration when calling 'no', expressed as a percentage of maximum acceleration.

DISCUSSION

Making a catch in baseball provides the fielding team with a unique strategic advantage. In the 1954 World Series, Willie Mays turned the odds in his favor by successfully intercepting Vic Wertz' towering smash. When interviewed about his performance, Mays stated: *"I knew I had the ball all the time"* (Willie Mays Interview -- Academy of Achievement (December 06, 2013)). As such, this memorable play (known as 'the catch') was contingent on Mays' perception of the affordance of catchability. In this study, we assessed whether the dominant account for the control of the forward-backward component of running to catch a fly ball (i.e. the OAC strategy) can be extended to include the affordance aspects of intercepting fly balls. Note that several accounts are available for the lateral component of running to catch fly balls, and the coupling of the lateral and forward-backward components (Chapman, 1968; Fink et al., 2009; McBeath et al., 1995; Mcleod et al., 2001; McLeod et al., 2006; Shaffer et al., 2003). Here, we restrict ourselves to the control of forward-backward running.

Chapman (1968) proposed that the rate of change of the tangent of the elevation angle of the ball is constant for the constant running velocity that would lead a fielder to the right place in the right time. Depending on the distance a fielder has to cover and the time that is available to do so, this constant running velocity can take on any value. Running velocity can be really low for fly balls that are easy to catch and really high for fly balls that are almost impossible to catch. Yet, in its origin, the OAC strategy provides no means for separating catchable from uncatchable fly balls, in part because there is no one-to-one relation from optical acceleration values to catchability. We reasoned, however, that the OAC strategy could still work for perceiving catchability if fielders' action boundaries are taken into account (Fajen, 2005a; 2005b; 2005c; 2007; Harrison, Turvey, & Frank, 2016). From this, the OAC strategy could still specify the affordance of catchability under specific circumstances. Either optical acceleration equals zero, indicating that a fielder will arrive at the right place in the right time to make a catch (i.e. the ball is catchable), or optical acceleration does not equal zero while a fielder is running to the best of his/her abilities, indicating that a fly ball is uncatchable. We found, however, that participants' judgments of uncatchable fly balls were not confined to these particular circumstances. In fact, participants rarely ran at maximum velocity or –acceleration while judging a fly ball to be uncatchable.

Whenever participants called 'no' their running velocity was often far from maximal; indeed participants could even be standing still while doing so. The same goes for running acceleration. Participants were hardly accelerating, or even decelerating, as they called 'no'. These findings contrast the aforementioned prerequisites for perceiving the affordance of catchability from the use of optical acceleration. One might argue however, that the decision to call 'no' is not reflective of the instant that a participant *actually* perceived a fly ball to be uncatchable. As such, perceptual judgments might have resulted from participants already having reached their locomotor maximum at an earlier moment. Yet, examination of the kinematic profiles revealed that this was not the case either: participants hardly ever reached their maximum running velocity or –acceleration before calling 'no'. Note that the maximum velocities and accelerations as determined for every participant might actually be underestimated. That is to say, we took their maximum values in the experiment, and it might well be possible that their actual maximum values were higher when allowed to run longer distances. Still, even so, the argument that participants did not reach their maximum running velocity or –acceleration before calling 'no' holds. These findings suggest that it is unnecessary for fielders to exert, or to have exerted, maximum locomotor effort when judging the catchability of a fly ball.

Knowing what one can and cannot do is essential to control of any type of behavior, including catching fly balls (Fajen, 2005a; 2005b; 2005c; 2007; Harrison et al., 2016). Fajen formalized the concept of affordance-based control with the task of braking a car to a safe stop (Fajen 2005a; 2005b; 2005c; 2007), arguing that affordance aspects of situations are part of the control of action. In this study, we advocate affordance-based control and aimed to extend its principles to the fly ball paradigm. Having established that the OAC strategy cannot be easily extended to include the affordance aspects of fly ball catching can be seen as a first step in doing so. One complication in making the next steps in developing the affordance-based account is that it is not clear how to characterize the affordance of catchability. One reason that using the OAC strategy did not work out very well was that this strategy yields no information on when an approaching fly ball would be landing where. This means that the task of identifying the affordance (i.e. the relation between ball-flight characteristics and player abilities) is not straightforward from a scientific point of view. A next step in the hunt for an affordance-based account, thus, might be an attempt to lay out the variables that combine to classify some fly balls as catchable and others as uncatchable. For present purposes, we have worked from the assumption that the 'no'-s of our participants were sufficiently accurate. Understanding how ball-trajectory characteristics combined with player abilities to yield the affordance of catchability would allow us to check this assumption. More importantly, however, it would possibly guide us to uncovering the information that people use to perceive the affordance of catchability of approaching fly balls. Finally, the temporal patterns that we observed when participants gave their 'no'-s might prove useful to arrive at a more precise characterization of the optical variables that they used. Potentially, the optics at the moment that (or just before) the moment the participants called 'no' can be used to identify the optical variable. For certain ball trajectories participants were quick to respond, for others they needed more time. Because we are able to determine time series of positions of ball and head, time series of optical variables can be computed. Scrutinizing the latter time series around the moments of calling 'no' might prove to be the way to uncovering the optical variable that is at the basis of knowing when a ball is not catchable.

All in all, although the OAC- or Chapman strategy, provides a parsimonious (and, as such, is the dominant) account for locomotor control in catching fly balls, it does not appear to be easily extended to include the affordance aspects of catching a fly ball. Although our analyses showed this to be necessary for the OAC strategy to deal with catchability, neither running velocity nor –acceleration was maximal whilst judging a fly ball to be uncatchable. As such, the OAC strategy appears to be unable to explain how the perception of catchability comes to be.

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IV

THE AFFORDANCE OF CATCHABILITY IN RUNNING TO INTERCEPT FLY BALLS

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How do outfielders control their locomotor behavior in running to catch fly balls? This question has been the topic of many empirical studies. Interestingly, a little addressed but highly relevant issue in this regard is that of the influence of perceived catchability on locomotor control. We examined what factors determine catchability and whether catchability can be reliably perceived. We had participants run to catch fly balls that could either be catchable or uncatchable. Participants performed two tasks. In the *catching task*, they were instructed to attempt to catch the ball and to keep running even when they felt that a ball was uncatchable. In the *judging task*, they were instructed to call 'no' as soon as they perceived a ball to be uncatchable. Using *Generalized Linear Mixed Effects Regression* (GLMER) on data from the catching task, we modeled catchability, identifying five behaviorally relevant agent-environment variables that together explained 84.4% of the variance in catching performance. Next, we examined whether judgments of catchability were accurate. Using the GLMER-model, the catchability of every fly ball in the judging task was predicted and subsequently compared with participants' judgments. Participants were able to correctly judge the catchability of a fly ball on 85.4% of the trials. Interestingly, participants' judgments of fly balls to be uncatchable most often were given only after they had started running. Present findings provide a valuable step towards the formalization of an affordance-based control strategy for running to catch fly balls.

INTRODUCTION

Athletes have a keen sense for what they can and cannot do. They are aware of their action possibilities and act accordingly. A nice instantiation of this can be seen from an outfielder running to intercept a fly ball. The primary goal of an outfielder is to make a catch in order to gain advantage over the batting team. However, this might not always be possible. Some fly balls are simply uncatchable. When an outfielder perceives a fly ball to be uncatchable, he or she would be wise to get the ball after the first bounce or have a teammate make the catch. Alternatively, when a fly ball is only just catchable, an outfielder might want to increase running speed to create a safe region. These considerations are part and parcel of the game of baseball and illustrate how locomotor behavior might be influenced by an outfielder's perceived action possibilities, that is, by his or her *affordances* (Fajen, 2005a, 2005b, 2005c, 2007; Fajen, Riley, & Turvey, 2008; Oudejans, Michaels, Bakker, & Dolné, 1996). Paradoxically though, at present, affordances have no part in models on locomotor control in running to catch fly balls (cf. Postma, Smith, Pepping, Andel, & Zaal, 2017). In this contribution we will present some initial steps towards the formalization of an affordance-based account of catching fly balls, one that is appreciative of the fact that, in the end, behavior is the realizing of affordances. By that, we touch upon one of the long-standing issues in the field of perception and action: The incompatibility of most existing models of control strategies with the theory of affordances (Barsingerhorn, Zaal, Smith, & Pepping, 2012; Fajen, 2007; Stoffregen, 2000).

The concept of affordance-based control is probably best illustrated by considering the braking paradigm. By studying the task of braking a car to a safe stop, Fajen (2005a, 2005b, 2005c, 2007) developed the concept of affordance-based control, in which affordances, rather than principles of error-nulling, are central to understanding control of human behavior. For decades, the prominent account of the control of braking has been the use of the $\dot{\tau}$-strategy (Kim, Turvey, & Carello, 1993; Lee, 1976; Yilmaz & Warren, 1995). As Lee (1976) demonstrated, by controlling the rate of deceleration of the vehicle such that $\dot{\tau}$[1] is kept equal at a value of -0.5, a motorist will come to a full stop right in time. Because the $\dot{\tau}$-strategy does not inform whether any difference between a current $\dot{\tau}$ and the value of -0.5 will be null-able given the motorist's action boundaries (i.e. the maximal rate of deceleration), Fajen (2005a, 2005b, 2005c, 2007) argued that this control strategy was mute on affordances. As an alternative, Fajen (2005a, 2007) proposed that braking is controlled by pursuing a ratio of ideal deceleration (i.e. the rate of deceleration that would require no additional braking adjustments to come to a safe stop at the mark) and maximum deceleration (i.e. the strength of the brake of the car). Safe braking is afforded for as long as ideal deceleration is smaller than maximal deceleration. In contrast, safe braking is no longer afforded if ideal deceleration supersedes maximal deceleration. At any moment in time, a driver can directly perceive whether safe braking is possible. Indeed, in braking a car to a safe stop, it has been shown that drivers shy away from having to apply maximal brake pressure. When ideal deceleration gets close to maximal deceleration, people tend to increase brake pressure in order to maintain a safe region (Fajen, 2005a, 2007).

[1] $\dot{\tau}$ is the first time-derivative of the ratio of the optical size of an object over its rate of optical expansion.

Until now, well-developed accounts of affordance-based control have been mostly concerned with braking (Fajen, 2005a, 2005c, 2005b, 2007; Harrison, Turvey, & Frank, 2016)[2]. We set out to extend the catalogue of affordance-based accounts to also include fly ball catching. Just as successful braking can be achieved in many ways (e.g., conservative braking versus aggressive braking), making a successful catch in baseball can also be achieved in many ways (Fajen et al., 2008). Outfielders might adhere to a just-in-time strategy, making sure that they get to the right place exactly in time. Alternatively, outfielders might also adopt a more safe strategy, making sure that they get to the interception location in a timely fashion, perhaps to prepare for the next move (for example, throwing the ball to the shortstop, who might in turn be in the position to tag out any potential runners).

An important reason to select fly-ball catching as task for developing an affordance-based control account is the availability of suitable models of its (locomotor) control. For the situation of fly balls approaching head on—the task adopted in this study—the prominent model is that of Optical Acceleration Cancellation (OAC). The OAC strategy amounts to attempting to keeping constant the optical velocity of the ball (e.g., Chapman, 1968; Fink, Foo, & Warren, 2009; McLeod, Reed, & Dienes, 2001, 2006; Michaels & Oudejans, 1992; Todd, 1981; Zaal, Bongers, Pepping, & Bootsma, 2012; Zaal & Michaels, 2003)[3]. Whereas the presence of optical acceleration (i.e. non-constancy of optical velocity) informs the fielder in which direction to change running speed, the OAC strategy does not include the control dynamics of these changes. That is to say, experiencing optical acceleration tells the fielder to slow down or speed up, but not by how much. Therefore, analogous to the $\dot{\tau}$-strategy, the amount of optical acceleration cannot be related with the fielder's action capabilities to simply reformulate the OAC model in affordance-based terms (Postma et al., 2017).

While the amount of optical acceleration is not informative of the locomotor adjustment that is required, or whether this adjustment is within a fielders' action capabilities, there are two specific circumstances under which OAC could be aligned with knowing the (un)catchability of approaching fly balls (cf. Fajen, 2007; Fajen, Diaz, & Cramer, 2011; Oudejans et al., 1996; Postma et al., 2017). First, clearly, a fielder knows that a fly ball will be *catchable* when optical acceleration equals zero. When that is the case, the fielder's locomotor velocity is such that he or she will arrive at the right place in the right time to make the catch. Secondly, a fielder knows that a fly ball will be *uncatchable* when detecting optical acceleration while already running at the maximum. When this is the case, the fielder's locomotor velocity is insufficient to get to the ball in time, and locomotor velocity cannot be increased. Following this line of reasoning, catchability might only be perceived under these specific circumstances. To test the latter possibility of OAC to be informative of uncatchability, Postma and colleagues (2017)

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[2] But see Fajen (2013) for an affordance-based control model for locomotion.

[3] The present study considers balls approaching fielders head on. When following the OAC strategy, a fielder attempts to keep a constant optical velocity, defined as the rate of change of optical position, which, in turn, is mathematically equivalent to the tangent of the elevation angle of the ball with the horizontal (e.g., Postma et al., 2014; Zaal et al., 2012; Zaal & Michaels, 2003). For fly balls heading off to the side, different strategies have been proposed, such as the Linear Optical Trajectory (LOT) strategy (McBeath, Shaffer, & Kaiser, 1995); the segmented Linear Optical Trajectory (SLOT) strategy (Shaffer, Krauchunas, Eddy, & McBeath, 2004); the Generalized Optical Acceleration Cancellation (GOAC) strategy (McLeod et al., 2006) and the Constant Optical Velocity strategy (COV) strategy (Marken, 2001; Shaffer, Marken, Dolgov, & Maynor, 2013, 2015). The latter strategy has also been implicated to account for locomotor behavior in running to catch fly balls that approach an outfielder head on (Marken, 2001). Note that in the COV strategy, optical velocity is defined as the rate of change of the elevation angle per se rather than the tangent of this angle. The COV strategy has been tested for intercepting objects that follow irregular and unpredictable flight paths (Shaffer et al., 2013, 2015), but not yet for fly balls.

had participants run to intercept both catchable and uncatchable fly balls, and instructed them to call 'no' immediately when they knew that a ball would be uncatchable[4]. When considering the running speeds of their participants at the moment of giving their 'no'-s, these turned out to be anywhere in the range from zero to maximum running speed, the latter observed only occasionally. Clearly, from the assumption that the judgments were relatively accurate, OAC does not seem to be the basis of knowing about fly balls' uncatchability.

The perception of catchability was also investigated in a series of studies designed to investigate the need for observer movement for accurate affordance perception (Fajen et al., 2011; Oudejans et al., 1996). Although Oudejans and colleagues (1996) concluded that moving helps to improve the accuracy of catchability judgments, Fajen and colleagues (2011) showed that a number of potential confounds could have been responsible for the differences in accuracy of affordance judgments in the original study. That is to say, they found no evidence for a need to move at all, let alone at maximum speed, for accurate catchability judgments. Interestingly, these studies also attempted to characterize the affordance of catchability. Both studies asked whether maximum running velocity or, alternatively, maximum running acceleration would best capture the action capability underlying the affordance of catchability. The results were inconclusive: none of these two variables clearly stuck out as the best characterization of a fielders running ability.

In the present contribution we set out to answer two questions in context of developing an affordance-based control model for catching fly balls: What characterizes the affordance of catchability of a fly ball? And can catchability be reliably perceived? To address these two issues, we designed an experiment in which participants were tested in a catching task and in a judging task. In both tasks, participants had to intercept tennis balls that could be either catchable or uncatchable. In the catching task, they were instructed to keep running even if they felt that an approaching ball would be uncatchable, and only stop when the ball was caught or had hit the floor. In the judging task, they were asked to call 'no' whenever they perceived a fly ball to be uncatchable (see also: Postma, den Otter, & Zaal, 2014; Postma et al., 2017; Shaffer & McBeath, 2002), after which they could stop running. We performed *Generalized Linear Mixed Effects Regression* (GLMER) on data from the catching task to examine what factors (e.g. flight time and passing distance) were related to the boundary between catchable and uncatchable fly balls. Second, we used this regression model to the data of the judgment task (i.e. within subjects) to establish how accurate the participants' judgments had been.

METHODS

Participants

Eight men and ten women, 19 to 24 years of age, volunteered to take part in the experiment. For inclusion in the experiment, participants were required to have at least 2 years of experience playing ball sports. All participants reported normal or corrected to normal vision. Prior to the experiment, all participants were informed about the procedure and gave their written informed consent. The experiment was approved by the Ethics Board of the Center

[4] Shaffer and McBeath (2002) applied a similar method, in a study addressing the control of the lateral component of running to catch fly balls.

for Human Movement Sciences (University Medical Center Groningen, University of Groningen, the Netherlands), and the protocol was in accordance with the Declaration of Helsinki.

Setup and apparatus

The experiment took place in a spacious, well-lit gymnasium (50×30×10m). Tennis balls were projected, using a pitching machine with adjustable pitch and power (Louisville Slugger, type UPM45 Blue Flame). The factory settings of the pitching machine only allowed for limited manipulation of the projection angle. Therefore, the pitching machine was modified to accommodate our needs. This was done by mounting the machine on a wooden board that could be placed under a particular angle using wooden blocks of different heights. The heights of the blocks were such that the machine could be tilted 10 to 40 degrees in increments of 5 degrees. This allowed us to devise the desired ball trajectories.

By varying both the initial position of the participant and the projection distance of the ball, passing distance (see Figure 1) could be manipulated. Participants were positioned 18 to 22 meters from the site of ball projection. The ball projection distances varied between 9 and 31 meters. Ball trajectories were not completely reproducible due to variability in ball delivery by the projection machine at the same settings: Projection distance could be manipulated with an approximate accuracy of 0.5 meter. The pitching machine was occluded from sight to prevent visual anticipation on the upcoming ball trajectory.

The experiment was recorded using an HD-camera (Canon Vixia, HF100 || JVC Everio, GZ-GX1) positioned perpendicular to the plane of ball projection. The camera was set to its minimal focal length to provide a wide angle of view (122° || 111°); this enabled us to fully capture both the kinematics of the ball as well as the kinematics of the fielder. A ×0.45 wide-angle adapter was used for the Canon Vixia to obtain the angle of view mentioned above. The camera was mounted on a tripod and was set to record at a frame rate of 25 || 29.97 frames per second. A fast shutter speed (1/200) was used to prevent motion blur.

Design

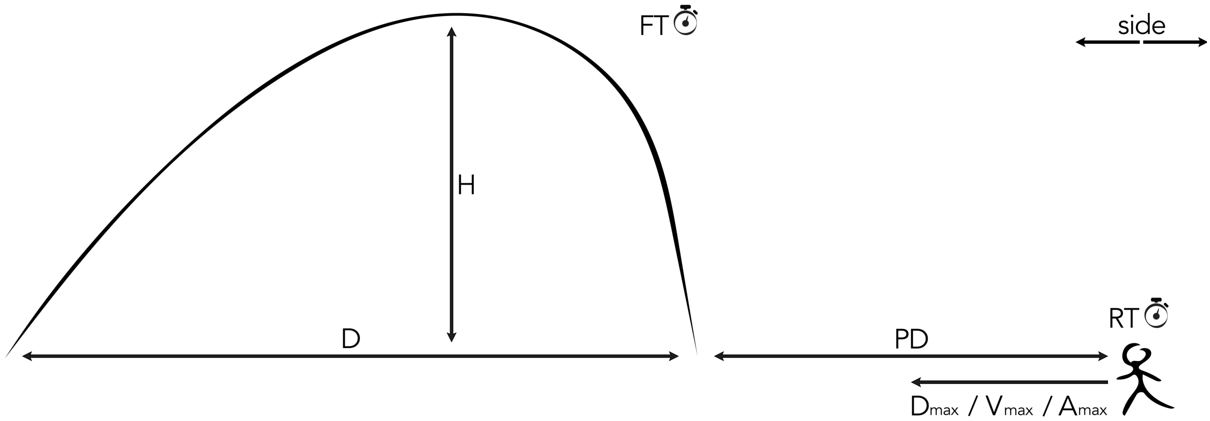
All participants were tested in two tasks: a *catching task* and a *judging task*. In both tasks, participants were required to intercept tennis balls that were projected along their sagittal plane (i.e. approaching head-on). Fly balls could be projected either behind (*back trials*) or in front of the initial position of the participant (*front trials*). Furthermore, the projected tennis balls could be either catchable (i.e. within locomotor reach of the participant) or uncatchable (i.e. beyond locomotor reach of the participant). In the catching task, participants were instructed to try their best to intercept as many fly balls as possible. Additionally, participants were required to keep running even when they felt a ball to be uncatchable, and only to stop running when they had caught the ball or after it had hit the floor. In the judging task, participants were also instructed to try their best to intercept as many fly balls as possible; However, participants were now required to call ‘no’ the instant they judged a ball to be uncatchable, after which they were allowed to quit running. There were no specific instructions given with regard to catching technique (i.e. underhand- or overhand catching). Participants started out randomly with either the catching task or the judging task.

Catchability was manipulated by varying the distance that a participant had to cover to make the catch (i.e. passing distance, see also Figure 1). The maximal height that was reached by the ball during flight was held roughly constant (M = 8.31m; SD = 0.58m), resulting in an average flight time of 2.53 seconds (SD = 0.10s) for all projected balls. To maximize uncertainty in catchability, we aimed for participants to be able to catch approximately half of the projected fly balls. This required us to tailor the test sets to the locomotor abilities of individual participants. To get an estimate of the participants' locomotor abilities, they received eight pretesting trials, randomly projected behind or in front of the initial position of the participant. For these eight pretesting trials, for fly balls projected in front, passing distance ranged from 7.5m to 10.5m, while for fly balls projected behind, passing distance ranged from 6.5m to 9.5m. Based on participants' performance on the practice trials, an appropriate test set was selected. Two participants received a test set that ranged in passing distance from 4 to 9 meters; one participant received a test set that ranged in passing distance from 5 to 10 meters; ten participants received a test set that ranged in passing distance from 6 to 11 meters; four participants received a test set that ranged from 7 to 11 meters and finally, one participant received a test set that ranged from 8 to 12 meters. All sets were designed to be symmetrical; that is, the range in which passing distance was varied was the same for front- and back trials. Furthermore, all sets were devised in such a way that the initial position of the catcher was not indicative for passing distance or passing side. Participants were unaware that the difficulty of the task was adjusted according to their performance in pretesting. After the pretesting trials, participants received two repetitions of 22 different block-randomized trials in each of both conditions, for a total of 88 trials (i.e. 2 conditions × 2 repetitions × 22 trials). At the start of each trial, the experimenter verbally cued the participant for ball delivery.

Data analysis

Video data were imported on a computer and converted to *.MOV files using QuickTime Player (v. 10.4). Subsequently, video files were cut to individual trials. The first frame associated with ball projection demarcated the start of a trial. The first frame associated with either a successful catch (i.e. the ball hitting the hand of the participant) or an unsuccessful catch (i.e. the ball hitting the floor), demarcated the end of the trial. In this definition, success was defined as the participant touching the ball before it hit the floor. Participants were unaware of this definition and were told that fumbles were not counted as successful catches. To capture the timing of calling 'no', Adobe Premiere Pro CC 2015 was used on the video data of the judging condition. The first frame associated with a participant calling 'no' was taken to represent the 'no' moment.

To retrieve the kinematics of both the ball and the participant, we digitized the planar coordinates of the ball and of the participant's head on a frame-to-frame basis using in-house developed software (NBody, v.09-13; E. Otten). Using a planar checkerboard pattern, lens distortion was calculated and corrected for. Since the digitization method for the ball differed from the digitization method for the participant, the procedure was performed in two steps. First, the position of the ball was determined by subtraction of subsequent frames. Differences between frames were highlighted after a trial was fully analyzed; subsequently, the trajectory of the ball was manually specified from the highlighted regions. Second, the head position of the participant was digitized using a custom-made shape recognition algorithm. By manually identifying the participant's head in the first frame of a trial, the position of the head could be digitized semi-automatically for the rest of the trial. Whenever the tracking algorithm was unable to establish the position of the participant's head, for instance, due to irregularities in the background, the position of the participant's head could be digitized by hand. The digital coordinates of the ball and the participant were transformed to real-world coordinates using a quaternion.



D	Distance	Total distance covered by the ball[1]
H	Height	Greatest height reached by the ball[1]
FT	Flight Time	Total time the ball was in flight[1]
PD	Passing Distance	Absolute total distance between the initial position of the participant and the landing location of the ball[1]
RT	Response Time	Total time from ball launch to the participant reaching $1ms^{-2}$
D_{max}	Locomotor Range	Greatest distance covered by the participant in any of the trials during the experiment[2]
V_{max}	Maximal Running Velocity	Greatest running velocity reached by the participant in any of the trials during the experiment[2]
A_{max}	Maximal Running Acceleration	Greatest running acceleration reached by the participant in any of the trials during the experiment[2]
side	Passing Side	Side to which the ball was projected relative to the initial position of the participant (i.e. in front or behind)
	Trial Number	The n^{th} trial presented to the participant
	Trial ID	Unique trial identifier
	Test Set	Test set presented to the participant
	Participant ID	Unique participant identifier
	Sex	The sex of the participant

[1] *Calculated with respect to eye height*

[2] *Separate measures were obtained for front-trials and back-trials*

Figure 1. Overview of the predictor variables considered for regression analysis of the catching data.

A fourth-order polynomial function was used to account for missing values in the ball data, whereas a smoothing spline was used to smooth and interpolate missing values in the participant data (smoothing parameter = 0.995). Subsequently, the data were used to calculate a number of variables that were considered to potentially relate to catchability (e.g. flight time and passing distance). An overview of all variables considered for analysis (including anthropometric measures) can be found in Figure 1. Note that *distance, height, flight time* and *passing distance* were calculated relative to eye-height. Furthermore, to account for any potential differences in running forwards and backwards, separate measures were obtained for front- and back-trials for *locomotor range, maximal running velocity* and *maximal running acceleration*.

We performed *Generalized Linear Mixed Effects Regression* (GLMER) on data from the catching task to assess what variables are related to catchability. Mixed-effects regression is an extension of ordinary (multiple) regression and is able to deal with datasets that contain nested dependencies. Repeated measures designs are well known to give rise to such dependencies since multiple measurements are obtained for each participant. This is also the case in the present study: Each participant was required to catch numerous fly balls. This means that part of the variation in catching-performance will probably be due to experimentally controlled factors, such as passing distance and flight time (fixed effects in GLMER) whereas part of the variation in catching-performance will be related to individual variation (random effects in GLMER). From the mixed-model framework, individual variation can be taken into account by allowing the model intercept and slope to vary over participants. Thus, in effect, mixed-effects regression allows individualized fits to the data without loss of statistical power. (For more detailed information on mixed models see: Tagliamonte & Baayen, 2012; Winter, 2013; Winter & Wieling, 2016).

The data were analyzed using the *glmer*-function of the *lme4* package (Bates, Maechler, Bolker, & Walker, 2015) of the R software package (R Core Team, 2016). We started out with an intercept-only model. Predictors were added in a forward step-wise fashion. To avoid multicollinearity, predictors that correlated highly ($\rho > 0.7$) were never included at the same time. Also, to prevent spurious relations in the GLMER-model, all continuous predictors were centered. Significant effects ($p < 0.05$), either fixed or random, were only included in the model if the improvement in the *Akaike Information Criterion* (AIC) was greater than 2. This procedure was performed until no further (significant) improvements could be obtained. Finally, the estimates of the model were validated using a bootstrap procedure (1000 iterations).

To assess a participant's accuracy in judging catchability, we originally had planned to directly compare judged catchability with actual catchability in a factorial design. However, the amount of variability in the ball launching apparatus precluded a simple comparison of identical trials in both tasks (i.e. the catching task versus the judging task). For this reason, we used the GLMER-model, constructed on data from the catching task, to predict catchability in the judging task (within subjects). Using said GLMER-model we could predict catchability on every trial of every participant. Next, the comparison could be made between judged catchability and predicted catchability. The congruency between these two measures was taken to represent the extent to which catchability could be judged.

RESULTS

The position of the ball could be established in 57.3% of all video frames and the position of a participant's head could be determined in over 99.7% of all video frames. Missing values were accounted for as detailed before. Trials in the judging task for which a participant failed to make the catch and also did not call 'no' were excluded from analysis ($n = 82$). In theory, participants could have called 'no' on a trial, while in the end still making the catch; this never occurred in our experiment. Finally, data from one participant were excluded from analysis because of technical difficulties while recording the experiment. Final analyses were performed on all remaining trials ($n = 1414$) of all remaining participants ($n = 17$).

As mentioned before, Generalized Linear Mixed Effects Regression was used to analyze the catching-data (see Figure 1 for an overview of all variables that were considered). Table 1 presents the significant effects of our final model. The model includes significant effects for passing distance, maximal height, response time and locomotor range, as well as Passing distance × Passing side and Response time × Passing side interaction effects. The probability for successful interception decreased with increasing passing distance (Figure 2A) and increasing response time (Figure 2C), whereas the probability for successful interception increased with increasing maximal height (Figure 2B) and increasing locomotor range (Figure 2D). Trials in which the ball was projected behind the initial position of the participant (*back trials*) showed to have a smaller chance to be successfully intercepted as compared to trials in which the ball was projected in front of the initial position of the participant (*front trials*).

Finally, participants exhibited variance in catching performance that could not be accounted for by the fixed effects: Some participants simply showed to be more proficient than others in catching fly balls, regardless of the test set they received. This is reflected in a significant by-subject random intercept (Table 1). The Best Linear Unbiased Predictors (BLUPs) can be observed from Table 2, listing individual adjustments to the overall model intercept for every participant. Overall, the model captured a high degree of variability in the outcome of the catching task. The model correctly classified the outcome in 84.4% of the trials (83,6% was due to fixed effects and 0.8% was due to random effects). The model had a sensitivity of 85.4% and a specificity of 83.0%. We will now proceed with a more detailed discussion of the factors that combine to characterize catchability.

Table 1. *Fixed Effects Structure (Top) and Random Effects Structure (Bottom) of the Mixed Effects Regression Model for Predicting Catchability*

fixed effects	**estimate (log odds)**	**SE**	**Z**	**p**	**95% CI Lower**	**95% CI Upper**
intercept	2.56	0.39	6.49	< 0.001	1.89	3.45
passing distance (m)	-1.73	0.18	-9.91	< 0.001	-2.14	-1.44
maximal height (m)	0.71	0.27	2.59	0.010	0.21	1.28
response time (s)	-4.20	1.24	-3.40	< 0.001	-7.29	-1.80
passing side (back)	-3.34	0.46	-7.35	< 0.001	-4.35	-2.56
locomotor range (m)	0.97	0.22	4.37	< 0.001	0.62	1.40
passing distance × side	0.56	0.17	3.25	0.001	0.21	0.99
response time × side	3.14	1.56	2.02	0.043	-0.05	6.41

random effects	**variance**	**p**	**95% CI Lower**	**95% CI Upper**
participant	0.71	< 0.001	0.31	1.19

Table 2. *Best Linear Unbiased Predictors for the By-Subject Random Intercept*

participant ID	**01**	**02**	**03**	**04**	**05**	**06**
logit adjustment	-0.24	-0.17	0.13	0.23	-0.30	-0.61
participant ID	**07**	**08**	**09**	**10**	**11**	**12**
logit adjustment	0.53	1.32	0.78	1.36	-0.69	-
participant ID	**13**	**14**	**15**	**16**	**17**	**18**
logit adjustment	-1.10	0.33	0.30	-0.81	-1.22	0.13

First, passing distance (moderated by passing side) showed to have a pronounced and significant effect on the catchability of a fly ball (Figure 2A). Passing distance was defined as the total distance that a participant had to cover to get to the future interception location with the ball (measured at eye-height). Following a logistic characteristic, the probability for successful interception decreased with passing distance. Balls projected at or near the initial position of the participant were typically catchable, whereas balls projected (very) far from the initial position of the participant were typically uncatchable. Note, however that the effects of passing distance on catching performance cannot be considered in isolation of the effect of passing side (Figure 2A). Whereas front trials and back trials followed a similar characteristic, clear differences can still be observed. The value for the intercept of the regression line is greater for front trials than for back trials, meaning that catching performance can be maintained over greater values of passing distance in front trials than in back trials. Furthermore, the slope of the regression line is steeper for fly balls projected in front of the participants than for fly balls projected behind the participants, implying that catching performance, on average, was more consistent in front trials than in back trials (Figure 2A).

Second, maximal height (i.e. the highest point of a ball's trajectory relative to eye height) also showed to hold a significant relationship with catchability (Figure 2B). Although, maximal height was not deliberately manipulated, the variation in this predictor still caused it to be significant (Table 1). A near-linear relationship can be observed for maximal height and catchability. As maximal height increased so did the probability of success. For the interpretation of the current findings, it is important to note that the highest point of a ball's trajectory is typically strongly related with the flight time of a ball. This was also found to be the case in the present experiment (ρ = 0.72). Consequently, to avoid multicollinearity between predictors, only one of these two predictors could be added to the model. We found that the AIC index was consistently lower for GLMER-models based on maximal height than for GLMER-models based on flight time, indicating that maximal height was more likely to capture the data than was flight time.

Third, response time had a significant influence on the catchability of a fly ball. Response time was taken to be the time between ball launch and a participant reaching an acceleration threshold of $1ms^{-2}$. The probability of successful interception decreased with an increasing response time. This effect was moderated by passing side (Figure 2C). In considering the partial effects for response time, it can be seen that the curve for front trials is notably higher than for back trials. However, care should be taken in interpreting this difference: In part, this difference is not an effect of response time per se, but rather an effect of the way partial effects are being calculated. Partial effects are calculated by cancelling the effect of all other predictors (i.e. setting other predictors to zero). When passing distance is set to zero, the difference between front trials and back trials, in terms of catching performance, is very pronounced (Figure 2A). So, in the context of response time, the difference in absolute height for front- and back trials is not very informative. When considering the course of both characteristics, however, it can be seen that the rate at which the dependent variable declines with increasing response time is different for front trials and back trials. For front trials, catching performance declines increasingly with increasing response times, while for back trials catching performance declines at a more constant rate (Figure 2C).

Fourth, the locomotor range of a participant had a significant effect on catchability. Locomotor range was the greatest distance covered by a participant in any of the trials during the experiment (determined for front- and back-trials separately). The probability of successful interception increased with locomotor range. Participants with a greater locomotor range showed better catching performance than participants with a smaller locomotor range. This is an interesting finding since the test sets that were presented to the participants were tailored to their performance on the practice trials. So, even though participants were challenged according to their (locomotor) abilities, locomotor range was still found to be a significant factor. Interestingly, the beneficial effect of locomotor range appeared to level off as it increased beyond the average locomotor range (Figure 2D). In this context, it should be noted that the factor of locomotor range is different from other predictors in at least two respects. First, locomotor range is highly specific to the current experimental setting as it relates strongly to the time available to make a catch (i.e. approximately 2.5 seconds in the current design). Second, locomotor range as a variable is only comprised of two unique values per participant (i.e. the greatest distance covered in any of the trials during the experiment determined for front- and back-trials separately); other predictors are formed by an array of data points per participant (i.e. one for each trial). Whereas, for example, passing distance varies from trial to trial, locomotor range was hypothesized to remain constant throughout the experiment on an individual basis.

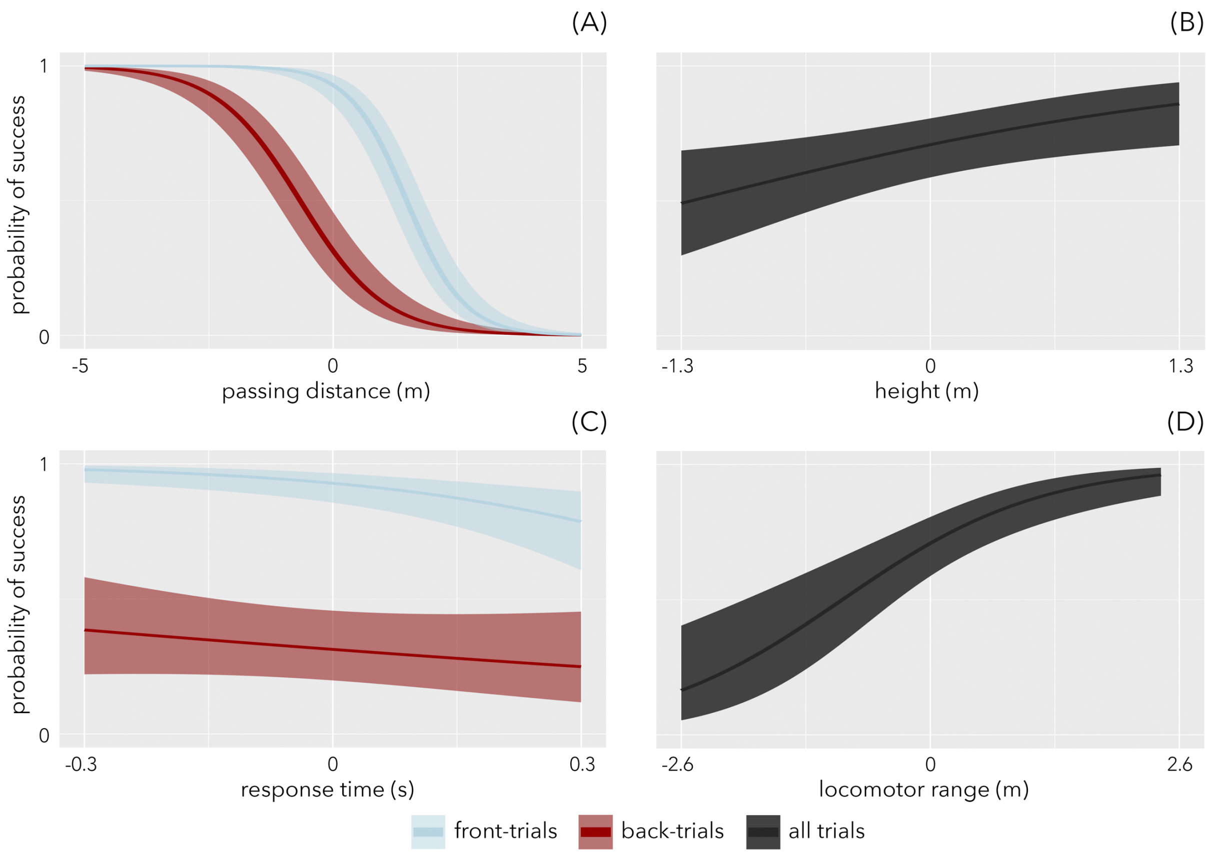


Figure 2. The partial effects in a maximum likelihood logistic mixed effects regression model, based on the catching-data, for the probability of successful interception in catching fly balls. The grand mean centered values (±2 *SD*) of the effect in question are on the abscissa, the response variable (i.e. probability of success in catching) is on the ordinate. Partial effects for passing distance (mediated by passing side) (a), maximal height (b), response time (mediated by passing side) (c) and locomotor range (d) are shown (solid lines). The shaded regions represent the 95% confidence interval.

Finally, we found passing side to be a significant predictor of catchability as well. The probability for successfully intercepting a fly ball was higher on front trials than on back trials. Furthermore, catching performance was more variable for back trials as compared to front trials. Also, passing side had a significant interaction effect with both passing distance and response time, both of which have been detailed above (also see Figure 2A and Figure 2C).

Catching versus Judging

As we mentioned above, the reliability with which catchability could be judged, could not be assessed by direct comparison of identical trials from the two different tasks (i.e. the catching task and the judging task). Variability in the ball launching apparatus made that ball trajectories could never be perfectly replicated. As an alternative to a direct comparison of trials with similar ball trajectories, we used the GLMER-model that we arrived at (using the data from the catching task) to predict catchability in the judging condition. In turn, a comparison could be made between catchability as predicted by the model and catchability as judged by the (same) participants. The congruency between predicted catchability and judged catchability was taken to be a measure of how well participants were able to judge the catchability of a fly ball. The overall congruency between predicted catchability and judged catchability was 85.4% (when considered separately for front trials and back trials, congruency was 87.8% and 82.8%, respectively). We found a hit rate of 0.79 and a false alarm rate of 0.11, resulting in a d' (i.e. sensitivity index) of 2.1. We also examined whether there was any bias towards calling 'no'; that is people might have called 'no' more often than would be expected based on predicted catchability. This however, was not the case with a response bias of 1.0.

The distribution of the times the 'no'-s were called, followed a bell-shaped pattern (Figure 3A). Participants were never faster to indicate that a fly ball was uncatchable than 1 second from ball launch. On average, participants called 'no' 2.00 s (*SD* = 0.38 s) after ball launch. An independent-samples *t*-test indicated that there was no significant difference [$t_{(243)} = 1.09$, $p = 0.227$, $d_s = 0.14$] in the timing of calling 'no' for front trials (*M* = 2.03 s, *SD* = 0.34 s) and back trials (*M* = 1.97 s, *SD* = 0.42 s). When the timing of calling 'no' was expressed as a percentage of total flight time (Figure 3B), participants judged a fly ball to be uncatchable on average at 74.4% (*SD* = 14.0%) of the ball's trajectory. Again, no significant differences [$t_{(243)} = 1.26$, $p = 0.210$, $d_s = 0.16$] were observed between front trials (*M* = 75.5%, *SD* = 12.1%) and back trials (*M* = 73.2%, *SD* = 15.7%).

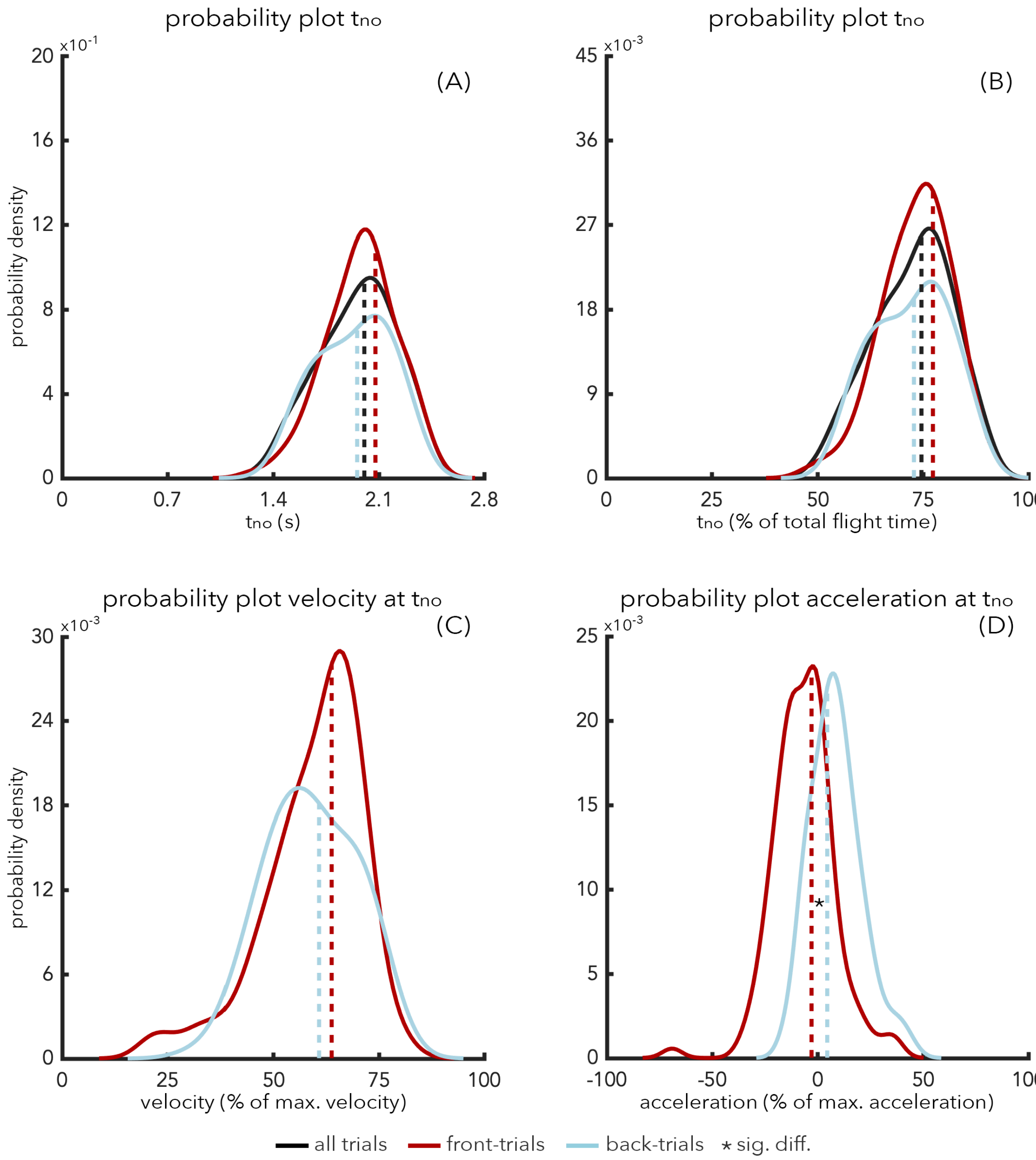


Figure 3. Probability density plots showing the relative likelihood distribution for relevant spatial-temporal characteristics related to calling 'no'. For every plot, the abscissa represents the range of relevant values associated with the variable in question and the ordinate represents the corresponding range of probability values. Solid lines represent probability density functions of the variable in question; dashed lines indicate the mean. Probability density plots are displayed for the absolute timing of calling 'no' (a); the relative timing of calling 'no' (b); running velocity at the time of calling 'no' (expressed as a percentage of maximal running velocity) (c) and for running acceleration at the time of calling 'no' (expressed as a percentage of maximal running acceleration). Different curves are plotted for front-trials (red lines), back-trials (blue lines) and, if applicable, all trials (black lines).

Participants' running speed and acceleration at the time of calling 'no' varied widely (Figure 3C-D). Participants ran on average at 62.9% (*SD* = 16.2%) and 61.2% (*SD* = 17.2%) of their maximum speed when calling 'no', in front and back trials, respectively. The difference was statistically not significant ($t_{(243)} = 0.77$, $p = 0.441$, $d_s = 0.10$). When considering participants' running acceleration while calling 'no', a significant difference [$t_{(243)} = -4.25$, $p < 0.001$, $d_s = -0.54$] was found between front trials (*M* = -3.8%, *SD* = 18.2%) and back trials (*M* = 5.9%, *SD* = 17.6%): Participants were on average decelerating at the moment of calling 'no' in front trials, while in back trials participants were on average accelerating. In this regard it is important to note, however, that the spread in running acceleration at the moment of calling 'no' was considerable both for front trials and for back trials. In 43.5% of the front trials, participants were in fact accelerating while calling 'no' and on 38.2% of the back trials participants were decelerating.

DISCUSSION

The present contribution considered the affordance of catchability in the context of running to catch fly balls. To this end, participants were required to try their best to intercept fly balls that could be either catchable or uncatchable. Using video-data, we were able to examine various agent-environment properties that held a potential relationship to the catchability of a fly ball. One of the main findings was that the catchability of a fly ball was best predicted by a combination of the following variables: passing distance, passing side, maximal height, response time and locomotor range. In combination, these properties were able to capture well over 80% of the variance in catchability. Furthermore, we were interested to know whether participants could reliably judge catchability (Postma et al., 2017). To address this issue, the experiment included, besides a catching task, also a judging task. A direct comparison between these two tasks was not possible due to the amount of variability in our ball delivery system. To circumvent this methodological difficulty, we first modeled catchability using the data from the catching task. Subsequently, we used this model to predict catchability in the judging task. Finally, a comparison could be made between judged catchability and predicted catchability. The congruence between predicted catchability and judged catchability was well over 80%, indicating that participants were able to reliably judge the catchability of a fly ball. This finding suggests that fielders are able to accurately perceive the affordance of catchability.

The OAC-strategy is an established account of locomotor control in running to catch fly balls that approach an outfielder head on (Chapman, 1968; Fink et al., 2009; McLeod et al., 2001, 2006; Michaels & Oudejans, 1992; Todd, 1981; Zaal et al., 2012; Zaal & Michaels, 2003). This strategy holds that an outfielder will arrive at the right place in the right time to make a catch by running so as to keep optical velocity constant. While in its original formulation, the OAC-strategy was not specifically designed to deal with the affordance aspects of running to catch fly balls, the principle of optical acceleration cancellation might still be used. The use of optical acceleration cancellation might inform an outfielder about catchability under two specific conditions: Either optical velocity is constant, informing the fielder that a fly ball will be catchable, or optical velocity is not constant and running velocity cannot be further increased, informing the fielder that a fly ball will be uncatchable. Thus, when based on OAC, a fly ball should only be judged to be uncatchable when the outfielder is running at maximal velocity (cf. Fajen, 2005c; Fajen et al., 2011; Oudejans et al., 1996; Postma et al., 2017). Yet, when people are instructed to judge a fly ball's catchability during an attempted catch, they are found to give their judgments while their running velocities, most of the times, are not at their maximum. Replicating the findings reported in Postma et al. (2017), participants in the present study were also running anywhere from about 20% to almost 100% of maximal running velocity at the moment of calling 'no'. Judgments of uncatchability appear to be inconsistent with OAC, and probably also with other existing error-nulling strategies on catching fly balls.

To study the affordance of catchability, we laid out the variables that combine to classify some fly balls as catchable and others as uncatchable. With only a handful of factors, we were able to reliably predict catchability. Like any affordance, the affordance of catchability is determined by the fit between properties of the environment on the one hand and properties of the agent's action system on the other hand (e.g., Fajen et al., 2008; Gibson, 1979; Richardson, Shockley, Fajen, Riley, & Turvey, 2008; Warren, 1984; Warren & Whang, 1987). In this respect, affordances can be said to have an environment side and an agent side of the coin. We will first discuss the environment-related factors of the affordance of catchability and subsequently the agent-related factors.

On the environment-side, we found passing distance (moderated by passing side) and maximal height to be significantly related with catchability. To reiterate, *passing distance* was the total distance a participant had to cover to make a catch, while *maximal height* was the highest point that a ball had reached during flight. In this respect, two things are important to recognize. First, the effect of *passing distance* was different for front trials and back trials: Not only were participants able to catch fly balls over a greater range of passing distances for front trials as compared to back trials, catching performance was also less variable for front trials as compared to back trials. The second thing to recognize is that the flight time of a ball is strongly related with its maximal height. While not perfectly so, maximal height is strongly related to flight time. As such, outfielders need to overcome a spatial-temporal demand if they want to make a successful catch.

As to the agent-related factors, we found response time (moderated by passing side) and locomotor range to be significantly related to catchability. *Response time* was the time it took a participant to start running and *locomotor range* was the greatest distance a participant had covered in any of the trials during the experiment, determined separately for balls projected behind and in front of the participants' initial positions. Again, two things are important to recognize. First, although we filed response time under the agent side of the affordance of catchability, response time is also strongly influenced by the flight characteristics of a ball. Maximal height, passing distance and projection distance all influence response time (Zaal, de Poel, Postma, Otten, & Pepping, 2017). That being said, response time has an important part in the affordance of catchability. While, maximal height (or analogously flight time) sets the time frame for interception, response time determines how much time can actually be used. If an outfielder would wait a long time to initiate movement, less time would be available for interception.

Secondly, locomotor range is somewhat of an oddball. In the present experimental setting, all fly balls had an approximate flight time of 2.5 seconds. Therefore, a participant's locomotor range represents the maximal distance that could be covered in that specific time frame. This complicates interpretation: It is unclear what a participant's locomotor range would have been if flight time would have been different[5]. Still, locomotor range rendered more intuitive predictors like *maximal running velocity* and *maximal running acceleration* insignificant upon inclusion in the model. As such, locomotor range captured more variance than the linear combination of its constituents. Thus, to better grasp the affordance of catchability, locomotor range seems an interesting variable to unpack. Although both variables did not emerge from the analyses (see also Fajen et al., 2011; Oudejans et al., 1996), it seems fair to assume that both maximum running velocity and acceleration are related with locomotor range. To unravel this relation, the velocity profiles of running would be helpful. These have been studied for sprinting: an athlete's horizontal velocity over time has been modeled with a mono-exponential equation (e.g., Cross, Brughelli, Samozino, & Morin, 2017; Furusawa, Hill, & Parkinson, 1927; Pantoja, Saez de Villarreal, Brisswalter, Peyré-Tartaruga, & Morin, 2016; Samozino et al., 2016; Simperingham, Cronin, & Ross, 2016)

$$v_h(t) = v_{h-max}\left(1 - e^{\frac{-t}{\tau}}\right), \tag{1}$$

in which v_{h-max} is the maximum velocity that an athlete can reach; t is time and τ is an acceleration-time constant, which reflects an athlete's ability to accelerate. Integrating this mono-exponential function over time will provide a characterization of locomotor range over time (cf. Samozino et al., 2016):

$$d_h(t) = v_{h-max}\left(t - \tau e^{\frac{-t}{\tau}}\right) - v_{h-max} \cdot \tau \tag{2}$$

While many studies have shown this relationship to hold for maximal sprinting under various conditions, a number of questions still remain. Most importantly, the model equations are valid for athletic sprinting, and differentiating *Equation 1* learns that the model assumes maximum acceleration at the start. While an athletic sprinting setting might allow for athletes' maximum acceleration to top right at the start of the sprint (e.g. due to the use of a starting block), this will presumably not be the case in the situation of running to catch fly balls. As such, maximum running velocity is explicitly part of the model equations (v_{h-max}) but maximum acceleration is not. Future studies will have to adapt the model equations for sprinting into equations capturing running to catch fly balls, including consideration of effects such as related with running backward versus forward. Ideally, a model should be developed that gives, at every moment in time, the maximum attainable running distance given current running speed, and, for instance, maximum running speed and acceleration. Future studies are needed to develop such a comprehensive model of locomotor range.

At this point, we have identified a number of agent-environment properties that can be used to reliably predict catchability for fly balls that approach an outfielder head on. However, this inventory of agent-environment properties should not be taken to represent the affordance of catchability just yet. An affordance is an invariant of a whole, rather than a sum of parts (Gibson, 1979). Moreover, percepts of action possibilities are not preceded by registering

[5] It is interesting to note that to some extent the same argument applies to maximal running speed and acceleration. The value for these variables is, much like the value for locomotor range, dependent on the time that is available for making the catch. For example, outfielders might be able to achieve greater running speeds when running to catch a fly ball than when running to catch a line drive.

abstract, extrinsic measures. Rather, perception of action possibilities is direct (Gibson, 1966, 1979; Michaels & Carello, 1981; Turvey, Shaw, Reed, & Mace, 1981). In the context of catching fly balls, this means that outfielders simply perceive catchability as is, not compiling it from a number of basic physical properties like flight time and passing distance. As such, in the future, we aim to capture the affordance of catchability in one unifying metric, much like has been done for reaching (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989), grasping (Cesari & Newell, 1999, 2000; Newell, McDonald, & Baillargeon, 1993), gap-crossing (Warren & Whang, 1987), sitting (Mark, 1987) and stair climbing (Cesari, Formenti, & Olivato, 2003; Warren, 1984). Thus, indeed, an additional step is needed.

As detailed above, to arrive at the affordance of catchability, agent-environment factors need to be combined to form a unifying metric. This procedure is much like preparing a meal for which you know the ingredients but not their respective quantities: We have identified a linear combination of physical factors that can be used to estimate catchability a posteriori, but we have yet to grasp the informational specification that informs about catchability on a moment-to-moment basis. In other words, an additional step is needed to characterize the affordance of catchability (as well as its optical specification). Focusing on fielders' judgments of catchability might prove helpful in this regard. More specifically, scrutinizing the time series around the moment that a fly ball is judged to be uncatchable might provide more insight into the nature of the affordance of catchability. In the judging condition, participants called 'no' to indicate that a ball was no longer catchable (more on this below), the temporal patterns surrounding this 'no' moment can subsequently be used to test a number of hypotheses regarding the structure of the affordance of catchability. Different metrics would lead to different predictions with respect to the timing of calling 'no'. For instance, if the affordance of catchability would be based on *required running velocity* (cf. Bootsma, Fayt, & Zaal, 1997; Peper, Bootsma, Mestre, & Bakker, 1994) that would give rise to a different patterning in calling 'no' than if the affordance of catchability would be based on *required running acceleration* (cf. Fajen, 2005a, 2005b, 2005c, 2007; Oudejans, Michaels, Bakker, & Dolné, 1996). However, before we can put these 'no'-moments to use, we needed to verify that people could reliably judge the catchability of a fly ball. If people would be unable to judge the catchability of a fly ball, it would make little sense to study the temporal structure in calling 'no'.

To test whether catchability could be reliably judged, the experiment included, besides a catching task, also a judging task. Using the GLMER-model derived from data of the catching task, catchability could be predicted for the judging task. The congruence between predicted catchability and judged catchability was well over 80%, indicating that participants were able to reliably judge the catchability of a fly ball. This finding suggests that fielders are able to accurately perceive the affordance of catchability. This is crucial because if participants were found to be unable to perceive the catchability of a fly ball, an affordance-based control strategy would not be viable.

In conclusion, in the present contribution, we studied the affordance of catchability. The aim was to characterize this affordance in behaviorally relevant agent-environment factors and to examine whether people can accurately judge the catchability of a fly ball. First, we were able to determine a set of variables that was able to distinguish accurately between catchable and uncatchable balls. Second, when considering the agent-related variables, the locomotor range turned out to capture more variance than (the linear combination of) maximal running speed and acceleration, which would explain why previous attempts to single out either maximal running speed or acceleration to determine the catchability of a fly ball came out inconclusive (Oudejans et al. 1996; Fajen 2011). Third, using the characterization of catchability, we were able to demonstrate that participants were able to judge a fly-ball's catchability correctly in over 85% of the trials. Finally, it is interesting to note that participants were typically already running at the moment that the judged a fly ball to be uncatchable (cf. Postma et al. 2017). Taken together, we hope that the present findings help to clear the way towards the formulation of a full-blown affordance-based control strategy for catching fly balls.

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V

DISTANCE OVER TIME IN A MAXIMAL SPRINT: UNDERSTANDING ATHLETES' ACTION BOUNDARIES IN SPRINTING

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Sprinting is a key endeavor in many disciplines of sport, including baseball. In the present study, the case of an outfielder running to intercept a baseball is of particular interest. In order to make a catch in baseball, an outfielder is oftentimes required to adjust his or her initial position to get to the right place in the right time. Whether this endeavor will be successful is dependent, inter alia, on the outfielder's locomotor abilities. The present study set out to study these locomotor abilities, aiming to map the relation among maximal running speed, maximum acceleration and the distance coverable over time. Thirty-three participants were recruited to perform a simple sprint task (4 conditions × 4 trials × 2 repetitions). The experiment consisted of a *forward-condition*; a *backward-condition*; a *compulsory-turn condition* and an *optional-turn condition*. Participants' position, velocity and acceleration data were obtained using a Local Positioning Measurement (LPM) system. This allowed for the investigation of a number of key issues. First, it was examined whether an inverse-linear relationship was apparent between running speed and acceleration in a maximal effort sprint, as was predicted from a prominent model on athletic sprinting. The present findings, however, show that this is not the case. Participants' velocity-acceleration profiles turned out to be markedly *non-linear*. To account for these non-linear patterns, a new macroscopic model on the kinematics of sprint running is proposed. Second, it was examined whether target distance was of influence on the evolution of participants' running speeds over time; the rationale for studying this was that outfielders might employ different pacing strategies depending on the total distance that needs to be covered to make a catch. Overall, no such effect on running velocity was present, except for a 'finish-line effect', for which participants showed to slow down near reaching the finish line. Finally, in light of catching baseballs that will ultimately fly overhead, it was examined whether outfielders would be faster making a turn or simply running backwards. For all target distances that were considered (3.75 – 30 meters), it was found that it was significantly faster to employ the former strategy than the latter. Ultimately, the aforementioned findings lead to the formalization of an Affordance-Based Control strategy for running to catch fly balls.

INTRODUCTION

Numerous situations in everyday life and sports require an agent to get to a certain place within a certain time. This is for instance the case in crossing the street in front of an oncoming vehicle and in running to catch a baseball. For an agent to be successful in either of these cases, he or she has to be sure that the spatial-temporal demands of the situation can be met: A pedestrian would not cross the street if that would mean getting hit by a car and an outfielder would not attempt to intercept a fly ball that is bound to leave the stadium. These situations illustrate the relevance of perceiving one's action possibilities, known as *affordances*, in performing everyday-life actions. For an agent to act adequate, accurate perception of affordances is key. The present study considers the affordance of the *catchability* of fly balls. As demonstrated in Postma et al., (2018), people are well able to distinguish catchable from uncatchable fly balls. This study also showed that the boundary between catchable and uncatchable fly balls is determined, on the one hand, by the distance that a player has to cover for the interception, combined with the time that the player has available for covering that distance. Importantly, the other side of the coin is how far a specific player can run in a certain time (or, put differently, how much time a player would need to cover a certain distance). The latter was captured as the *locomotor range* in the Postma et al. (2018) study. In the present study, we attempt to unpack this locomotor range, and study its relation with variables such as players' maximally attainable running velocities and accelerations.

Catching a fly ball involves getting to the interception location before the ball does. The control of running to catch fly balls has been considered in a fair number of studies. For fly balls approaching head on (i.e. requiring forward or backward running exclusively), the prominent model in the literature states that players zero out optical acceleration (e.g. Chapman, 1968; Fink, Foo, & Warren, 2009; McLeod, Reed, & Dienes, 2001, 2006; Michaels & Oudejans, 1992; Todd, 1981; Zaal, Bongers, Pepping, & Bootsma, 2012; Zaal & Michaels, 2003). For fly balls that also require a lateral component of the running, several alternatives have been proposed and tested (most notably, keeping a linear optical trajectory—McBeath, Shaffer, & Kaiser, 1995; Shaffer, Krauchunas, Eddy, & McBeath, 2004—keeping a constant bearing angle—Chapman, 1968—or keeping a constant optical velocity—Marken, 2001; Shaffer, Marken, Dolgov, & Maynor, 2013, 2015). All these models, however, ignore the effects that a boundary of catchability can have on the running behavior (cf. Postma, Lemmink, & Zaal, 2018; Postma, Smith, Pepping, Van Andel, & Zaal, 2017). Thus, an alternative to the existing models would be a model of affordance-based control of running to catch fly balls (cf. Fajen, 2005, 2007). In developing such model, an important step is to characterize the boundary between catchable and uncatchable fly balls.

A number of studies (Fajen, Diaz, & Cramer, 2011; Oudejans, Michaels, Bakker, & Dolné, 1996; Postma et al., 2018) has addressed the affordance of the catchability of fly balls. All of these studies, to some extent, also attempted to relate the boundary between catchable and uncatchable fly balls with players' maximum running velocities or accelerations and were unsuccessful in definitively pinpointing either of these two player-related factors to the players' locomotor ranges. That is to say, in their analyses, Oudejans and colleagues determined the boundary between catchable and uncatchable fly balls (or fly balls judged as such). Although drawing this boundary, per participant, as a function of to-be-covered distance over time (i.e. required-velocity) or over time squared (i.e. required-acceleration) captured the observed boundaries better than using required distance per se, the fits based on the velocity and on the acceleration measures were of similar quality. Fajen et al. (2011), in a follow-up on the Oudejans et al. study, introduced an alternative to the required-velocity measure. They determined, per participant, at each point in time the greatest distance that the participant had covered. They used this to compute, for each trial, the difference in the time needed to cover the distance to the ball's landing location and flight time of the ball, which was called the time-to-spare. Using this time-to-spare as a basis for drawing the boundaries between catchable and uncatchable balls led to similar results as using required velocity as the basis (for the conditions that were compared, see Fajen et al., 2011). Unfortunately, for the present purposes, no direct comparison of the goodness of fit of both ways to determine the boundary between catchable and uncatchable balls was presented. Finally, Postma and colleagues (2018) used the maximum distance that a participant had been able to cover during the flight time of the balls (which was roughly constant in their experiment) for characterizing the boundary between catchable and uncatchable fly balls. Their analyses showed that this locomotor range led to better fits than required velocity or required acceleration. Taken together, these studies indicate that the distance that players can run in a certain time does not seem to be determined exclusively by either the maximum velocity or the maximum acceleration that they are able to reach. Still, both variables seem to play a role in defining this maximum distance. The present study was designed to map the relation among maximum velocity, maximum acceleration and the distance coverable within a certain time.

Studies of (professional) sprinting and track running have considered the effects of a person's maximum running speed and acceleration on the running kinematics. A prominent model on locomotor performance in maximal-effort sprints stems from early experiments of Hill and colleagues (Furusawa, Hill, & Parkinson, 1927; Hill, 1927), aimed at quantifying the dynamics in sprint running. Hill derived a mono-exponential relationship that very well captures the velocity-time relationship of an athletes' Center of Mass in maximal-effort sprinting:

$$v_h(t) = v_{h-max}\left(1 - e^{\frac{-t}{\tau}}\right) \tag{1}$$

Equation 1 provides an athlete's velocity, as a function of time, ($v_h(t)$). Where velocity is limited by two factors: The maximal running velocity that an athlete is able to develop (v_{h-max}) and the athlete's ability to accelerate over time, which is reflected by acceleration-time constant τ. Many studies have (indirectly) demonstrated that Hill's mono-exponential function captures the velocity profile for maximal-effort sprinting very well (e.g. Cross, Brughelli, Samozino, & Morin, 2017; Greene, 1986; Pantoja, Saez De Villarreal, Brisswalter, Peyré-Tartaruga, & Morin, 2016; Samozino et al., 2016; Simperingham, Cronin, & Ross, 2016; Volkov & Lapin, 1979). Integrating *Equation 1* over time provides a characterization of maximal displacement over time (i.e. locomotor range) in a maximal-effort sprint:

$$d_h(t) = v_{h-max}\left(t - \tau e^{\frac{-t}{\tau}}\right) - v_{h-max} \cdot \tau \tag{2}$$

Differentiating *Equation 1* on the other hand, provides a characterization of acceleration over time in a maximal-effort sprint:

$$a_h(t) = \frac{v_{h-max}}{\tau} e^{\frac{-t}{\tau}} \qquad (3)$$

Examining the set of *Equations 1-3,* it is clear that the model proposed by Hill assumes that an athlete's maximum acceleration equals v_{h-max} over τ, and that this maximum acceleration is seen right at the start of the run (i.e. $t = 0$). Furthermore, the relation between velocity (*Equation 1*) and acceleration (*Equation 3*) is linear, with a negative slope of -1 over τ. Note, however, that the model was developed for athletic sprinting. The present study was designed to determine the velocity-acceleration relation in a situation more closely resembling running to catch fly balls. That is to say, we will consider running, but for example starting without the starting blocks used in athletic sprinting. We expect that this will mean that players will not reach their maximum acceleration immediately at the start but probably somewhat later in the run. The implication of this would be that the relation between acceleration and velocity when asking players to run at their maximum abilities will not be entirely linear. Finally, we will also consider the situation that players run backwards or turn to run to a place that was initially behind their back. Obviously, this situation models what happens when players are faced with fly balls that are heading to the field behind their backs.

Mapping the relation between velocity and acceleration of a maximal sprint will allow us to determine the locomotor range in any situation that the player finds him or herself. At some specific moment in time, a player has a certain velocity (smaller than the maximum velocity). With the known relation (specific for this player), every velocity comes with a maximum acceleration. The maximum distance that the player can cover in a certain time is determined by his or her current velocity and his or her individual velocity-acceleration relation. We designed a fairly straightforward experiment in which participants were required to perform maximal-effort sprints. We had our participants perform forward sprints, backward sprints, sprints in the backward direction with a compulsory turn directly at the start, and backward sprints with an optional turn.

METHODS

Participants

Thirty-three people (30 men and 3 women) participated in this study. On average, participants were 21 years old (*SD* = 1.2). Participants were healthy individuals and reported no injuries that could affect their performance during the experiment. Prior to the experiment, all participants were informed about the procedure of the experiment both in writing and oral. The experiment was approved by the Ethics Committee of the Center for Human Movement Sciences (University Medical Center Groningen, the Netherlands), and the protocol was in accordance with the Declaration of Helsinki.

Setup and apparatus

The experiment took place on one of the practice fields of a professional soccer club (FC Groningen, The Netherlands). The experiment was performed on artificial turf with infill of granules of rubber. Participants were required to bring footwear specially designed for playing on such fields. When participants were not in possession of such footwear, the experimenters provided it for them.

Participants were all assigned an individual lane in which they could perform the sprints. Every lane was exactly 5 meters wide. Pylons along the long end of the lanes demarcated different target distances: 3.75, 7.5, 15, 30 and 60 meters. Note that the series of target distances is not random; rather, it is a geometric series with a common ratio of 2. The starting line was the same over all participants and trials and was set at 0 meters. Right behind the starting line, at the centerline of every lane, a pylon was positioned at minus one meter.

Position data were recorded using the Local Positioning Measurement (LPM-) system (Inmotio Object Tracking B.V., Amsterdam, The Netherlands) at FC Groningen. In principle, the LPM-system functions much like a *frequency-modulated continuous-wave bi-static radar* system (Stelzer, Pourvoyeur, & Fischer, 2004). The system is comprised of 10 base-stations and a number of transponders that can be tracked simultaneously. The base-stations trigger lightweight, wearable transponders on the field and in response the transponders emit an electro-magnetic signal. Participants' local positioning measurements are obtained on the basis of differential time-of-flight analysis and trilateration. The LPM-system is reported to be accurate in the range of a few centimeters also depending on participants' instantaneous dynamics (Frencken, Lemmink, & Delleman, 2010; Ogris et al., 2012; Pfeil, Schuster, & Stelzer, 2013; Stelzer et al., 2004). The LPM-system has an effective sampling frequency of 1000Hz, which is divided among the number of active transponders on the field. Every participant was equipped with a unique transponder. In total, there were never more than 16 active transponders on the field[1]. As such, the sample frequency of the system was never less than 62.5Hz. In addition, two video cameras recorded the experiment: One camera provided close-up footage of the starting line, the other captured the entire field. The camera that made close-up footage of the field was primarily used to record the starting signal for later analysis. Both cameras were Full-HD and recorded the experiment at 30Hz.

Design

The experiment had a repeated-measures, block-randomized design (4 conditions × 4 trials × 2 repetitions), as such participants performed a total of 32 maximal-effort sprints over four different conditions. In the *forward-condition* participants were required to cover different distances (i.e. 7.5, 15, 30 and 60 meters) as fast as possible, sprinting forwards. In the *backward-condition* participants were again required to cover different distances (i.e. 3.75, 7.5, 15 and 30 meters)[2] as fast as possible, however they were now required to do so sprinting backwards. In the *compulsory-turn condition* participants started out as in the backward-condition but were now required to make a swift turn after the starting signal had been given; thus, turning around, aligning the body with the direction of travel. For the compulsory-turn condition, participants were required to cover the same distances as in the backward condition. Finally, in the *optional-turn condition* participants were required to cover the same series of distances as in the backwards- and compulsory-turn condition and were again required to line up at the starting line in a backwards position. However, for the optional-turn condition, participants were now free to perform the sprints as they deemed fastest: Either

---

[1] One reference transponder with known location was always active for the LPM-system to function optimally.

[2] Note that the series of target distances for backward sprinting is slightly different from the series for forward sprinting. We reasoned that outfielders in baseball would never run 60 meters backwards to make a catch.

sprinting backwards or making a turn. Participants were allowed to pick a different strategy for every trial.

Procedure

The conditions were presented in a fixed sequence: Participants started out with trials from the forward-condition, followed by trials from the backward- and the compulsory-turn condition to finally perform the last eight trials from the optional-turn condition. Trials from the backward- and the compulsory-turn condition were intermixed and presented in alternating order. In baseball, outfielders are observed to keep an eye on the ball while running to make a catch (Oudejans, Michaels, Bakker, & Davids, 1999; Postma, den Otter, & Zaal, 2014). To mimic this situation for trials of the backward-, the compulsory-turn and the optional-turn condition, brightly colored pylons were positioned one meter behind the starting line of every lane; participants were empathically instructed to continuously focus their gaze on their pylon while performing the sprints. This required participants to look over their shoulder whenever they made a turn. To make sure that participants would keep up their efforts until they actually reached the finish line, they were instructed to keep running (backwards) until they had the designated finish pylons in their (peripheral) sight.

For all conditions, participants were required to start from standstill in an upright position with both feet positioned directly underneath their shoulders. When the starting signal was given, they were required to start sprinting immediately. The starting signal was an auditory cue, produced by striking two wooden planks forcefully against each other. This was done out of sight of the participants so no visual anticipation on the start-signal would occur. At the same time, the wooden planks served as a visual cue that could be used in data analysis to demarcate the start of each trial. All trials were presented in block-randomized order. In between trials, participants were given three minutes rest to allow for sufficient recovery. Also, to avoid injuries, participants were required to perform a ten-minute, moderate intensity warm-up prior to the experiment.

Data analysis

All data were sent in real time to the on-site LPM-server using glass fiber technology. Position data were filtered, smoothed and if necessary, interpolated using an integrated Kalman filter (Ogris et al., 2012; Stelzer et al., 2004; Stevens et al., 2014). Velocity- and acceleration data were smoothed using a gaussian filter. For analyses using the Generalized Additive Mixed Modelling framework (see below) unfiltered velocity and acceleration data were used to reduce effects of autocorrelation. The position-data, along with some auxiliary data, like participants' transponder ID's, were exported to *.csv-files and imported into MATLAB (MathWorks R2015b). The data were cut to individual trials. We intended to use the visual cue, given by one of the experimenters on the field, to demarcate the beginning of each trial, however, due to technical difficulties, this was not viable. With the LPM-software, events of interest could only be marked with limited temporal accuracy (i.e. accurate to about ± 200-300ms). Therefore, the start of every trial was taken to be the moment a participant reached a running velocity greater than 1 ms^{-1}. As such, the start of every trial was determined individually, rendering response time to be irrelevant for further analyses. The end of every trial was taken to be the instant participants reached the total distance they had to cover (i.e. when they reached the finish line).

Determining linearity between speed and acceleration

As a first objective, we set out to examine whether a linear relationship exists between running speed and acceleration, as would be predicted from Hill's (Furusawa et al., 1927; Hill, 1927) mono-exponential relationship on athletic sprint running (*Equations 1 and 3*). Running speed and -acceleration were calculated by differentiating participants' position-data, no additional smoothing was performed in doing so. *Generalized Additive Mixed Modelling* (GAMM) was used to test for linearity between running speed and -acceleration. GAMMs is a powerful and flexible regression technique (Hastie & Tribshirani, 1990; Wood, 2017). As an extension of mixed-effects regression, it is able to take into account the (dependency) structure of the data. In our case, participants ran various distances multiple times and therefore not all trials were independent. Mixed-effects regression (and GAMMs by extension) is able to bring such dependencies into the model and therefore the *p*-values will not be overconfident (i.e. too low). Furthermore, in contrast to ordinary (multiple) linear regression, GAMMs explicitly allow for nonlinear relationships. Importantly, the random-effects structure in GAMMs can incorporate nonlinearities through so-called factor smooths (which are analogous to both random intercepts and random slopes in the linear mixed-effects regression case). Consequently, GAMMs are able to deal with nested data structures in a principled manner, as individual variability is taken into account in assessing the (fixed-effects) model estimates. Finally, GAMMs (as implemented in the R package *mgcv*—Wood, 2003, 2004, 2011, 2017; Wood, Pya, & Säfken, 2016) are able to correct for autocorrelation in the residuals. Autocorrelation in the residuals means that the residuals (i.e. the differences between the model prediction and the actual values) at time point $t + 1$ can be predicted to a certain extent on the basis of the residuals at time point t. If autocorrelation is present, this means that the residuals are not independent. And this dependency needs to be corrected for in order to obtain adequate *p*-values.

As indicated, a distinct advantage of the Generalized Additive Mixed Modeling framework is that it relaxes the assumption of linearity. Frequently, the relation between the dependent variable and independent variables is not linear. Yet, conventional regression techniques typically do not allow for departures from linearity, unless the shape of the nonlinearity is explicitly specified a priori (e.g., quadratic or logarithmic functions). With GAMMs, however, the experimenter can estimate an unspecified nonlinear pattern from the data. Rather than fitting the best nonlinear pattern, GAMMs penalize nonlinearity in order to prevent overfitting. The result of this approach is that GAMMs will only identify a nonlinear pattern if there is enough support for its presence in the data (which is also validated internally via cross-validation). One approach to formally test for linearity using GAMMs is to fit and compare two models: One for which the relationship between the dependent and the independent variable is strictly allowed to be linear and one for which nonlinear relationships are also allowed.

For each of the four target distances in the forward-condition[3], both a linear and a nonlinear model were created. The model specification for the simple, linear model and the more complex, nonlinear model was the same for all target distances:

[3] The inverse linear relationship between running speed and -acceleration was only explicitly hypothesized for forward running, as such only trials from the forward-condition were considered.

```
m.linear = bam(acc.norm ~ vel.norm +
       s(vel.norm, pp, bs = "fs", m = 1), data = dat, method = "ML")

m.nonlinear = bam(acc.norm ~ s(vel.norm, k = 10) +
       s(vel.norm, pp, bs="fs",m=1), data = dat, method = "ML")
```

In these model specifications, the function-call `bam` is used to fit a generalized additive model to dataset `dat`. To test for linearity, only the best trial of every participant was considered. This was done, so that participants' velocity profiles could be normalized in order to prevent spurious fits. In both models, normalized acceleration (`acc`) is dependent on the normalized velocity profile (`vel.norm`). In the first model (`m.linear`) however, acceleration is linearly dependent on running velocity, while in the second model (`m.nonlinear`) acceleration is potentially nonlinearly dependent on running velocity. This is specified by: `s(vel.norm, k = 10)`, indicating that acceleration is allowed to be fit by a (nonlinear) smoothing function consisting of a maximum of 10 basis functions (`k = 10`). The `k`-parameter determines the maximum amount of smoothing that is allowed for fitting. Furthermore, both models include a random-effects structure specified by: `s(vel.norm, pp, bs = "fs", m = 1)`. Utilizing so-called *factor smooths* (`bs = "fs"`) potential non-linear differences over `vel.norm` with respect the general pattern of `vel.norm` can be modelled for each of the participants. Meaning that variation related to experimentally controlled factors (fixed effects in GAMMs) can be disambiguated from variation related to individual participants (random effects in GAMMs), thus allowing for individualized fits to the data without loss of statistical power. The term `m=1` indicates that the wigglyness for fitting individual curves is limited through a process of cross validation, effectively avoiding overfitting the data. Finally, both models were fit using maximum likelihood estimation `(method = "ML")`, this allowed for direct model comparison using the function *compareML* from the *itsadug*-package (van Rij, Wieling, Baayen, & van Rijn, 2017). With *compareML* the goodness-of-fit of two models is assessed in relation to their respective complexity, for example on the basis of the Akaike Information Criterion (AIC; Aike, 1974). For present purposes, a reduction in AIC of at least 2 units was required to select the more complex nonlinear model (cf. Postma et al., 2018; Wieling, 2018; Wieling, Montemagni, Nerbonne, & Baayen, 2014). To account for alpha-inflation due to multiple testing, a Bonferroni correction was applied. For more information on the mixed model framework see for example: Tagliamonte & Baayen, 2012; Wieling, 2018; Winter, 2013; Winter & Wieling, 2016.

Determining the effect of target distance on participants' velocity profiles

Another issue that we wanted to address was about the role of target distance in running behavior. People might cover certain distances differently depending on the total distance that needs to be covered. In our experiment for instance, participants might have covered the first 7.5 meters of a 15-meter dash differently from the first 7.5 meters of a 60-meter dash. As such, we checked for differences in participants' velocity profiles for different target distances using GAMMs. From the Generalized Additive Mixed Modelling framework, it is possible to identify the range over which two different (nonlinear) patterns are significantly different. As such, GAMMs are perfectly suited to test for differences in velocity profiles for different target distances. The velocity profiles over the first 7.5 meters of all target distances were compared; the velocity profiles over the first 15 meters of all but the 7.5-meter target distance were compared and the velocity profiles over the first 30 meters of the 30-meter dash and the 60-meter dash were compared. All trials of all participants were considered. To account for multiple testing, a Bonferroni correction was applied.

Determining the effect of turning on sprint times for targets behind participants' back

The final part of the data analysis is focused on making the comparison between the *backward-condition* and the *compulsory-turn condition*. When players are faced with fly balls that are heading to the field behind their backs, they might simply run backwards, or they may be forced to make a turn. Since the act of turning around might take some (valuable) time, the former strategy might actually be faster over shorter distances. As such, the goal of this comparison was to examine for which distances it would be faster to simply run backwards and for which distances it would pay off to make a turn. After having compared sprint times for the backward-condition and the compulsory-turn condition, we examined whether participants opted for the faster strategy when given freedom of choice in the optional-turn condition. To establish whether or not it would be faster to make a turn, we performed a paired-samples t-test on the average sprint times for each target distance ($\alpha = 0.05$). We used a Bonferroni correction to account for alpha-inflation. After having established what strategy was faster, we simply scored which strategy was used by participants on a trial-by-trial basis.

RESULTS

For final analysis, data from two participants were excluded: Data from one participant was incomplete due to technical difficulties related to one of the LPM-transponders and one participant had to quit the experiment prematurely due to an unreported, pre-existing hamstring injury. As such, final analysis was performed on data from all trials of the remaining 31 participants.

Linearity of running speed and -acceleration

As a first objective, we set out to examine whether the presumed inversed linear relationship between running speed and -acceleration in a maximal-effort sprint was in fact apparent. Using GAMMs, both a linear and a nonlinear model were fitted to data from the forward condition. For each of the four target distances (i.e. 7.5, 15, 30 and 60 meters) it was found that the nonlinear model provided a significantly better fit to the data than its linear counterpart (taking model complexity into account). For the 7.5-meter dash, the difference between the two models was found to be significant at: $\chi^2(1) = 143, p < 0.001$; for the 15-meter dash this was found to be significant at: $\chi^2(1) = 155, p < 0.001$; for the 30-meter dash this was found to be significant at: $\chi^2(1) = 151, p < 0.001$ and for the 60-meter dash this was found to be significant at: $\chi^2(1) = 226, p < 0.001$. Clearly, a nonlinear relationship exists between running speed and -acceleration in a maximum-effort sprint (see also *Figure 1*), at least for target distances up to 60 meters. In the next section, we will examine whether target distance is of influence on the way participants perform their sprints.

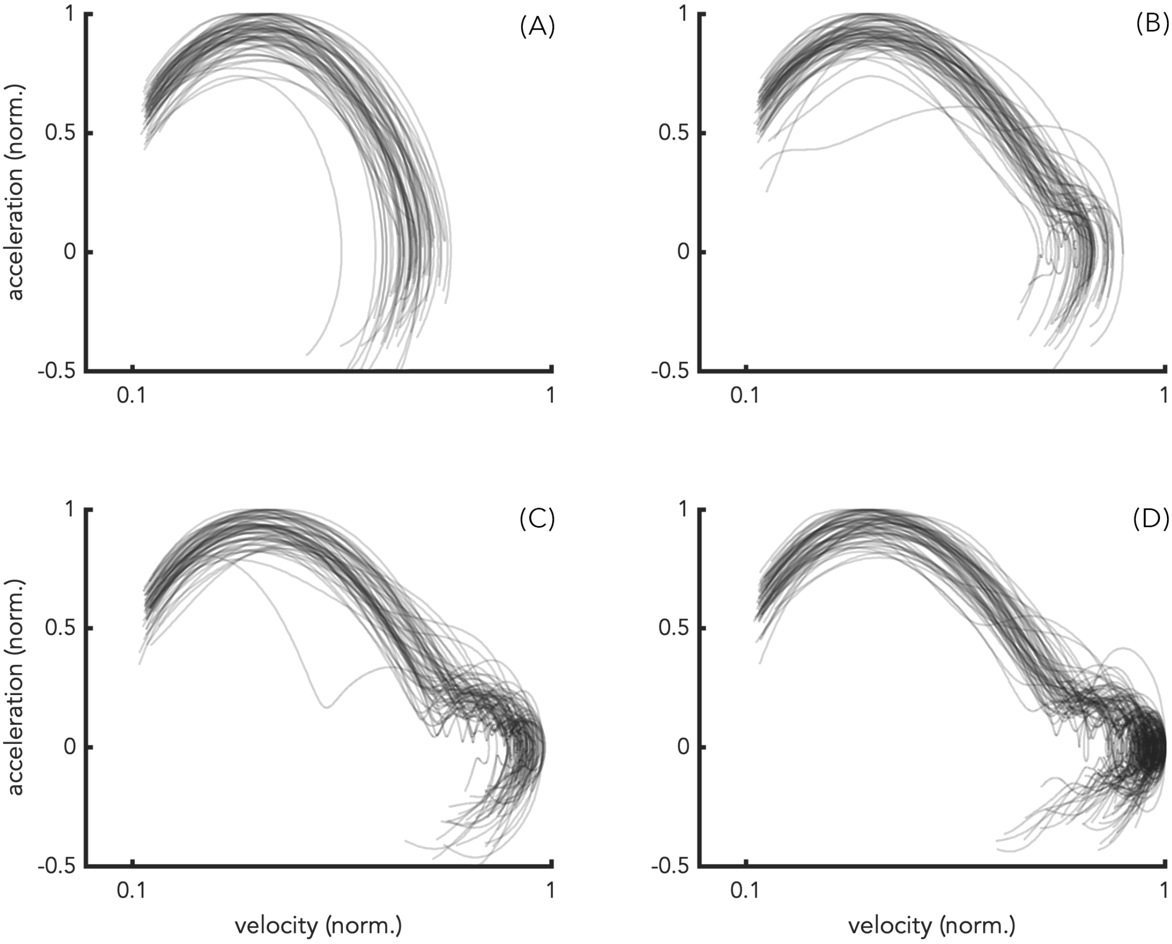

Figure 1. Sprint profiles from the forward-condition (condition 1). Running velocity is on the abscissa and running acceleration is on the ordinate. Both running velocity and -acceleration have been normalized by scaling all values to participants' maximal running velocity and -acceleration, respectively. The velocity-acceleration profiles are split out by target distance: Panel A represents all trials from the 7.5-meter dash; panel B represents all trials from the 15-meter dash; panel C represents all trials from the 30-meter dash and panel D represents all trials from the 60-meter dash.

The effect of target distance on participants' velocity-profiles

Having established that a nonlinear relationship exists between velocity and acceleration for maximal-effort sprinting in a baseball setting, we set out to examine whether target distance was of influence on participants' sprint behavior. Subtle differences might exist for the way outfielders cover different distances: Distinct pacing strategies may be used for various target distances. To test this presumption, we constructed generalized additive models to make direct comparisons between comparable distances of different target distances. As an illustration of this modeling approach, *Figure 2* shows velocity profiles of the first 7.5 meters of all trials of the *forward-condition*, split out by target distance. The translucent dots represent running velocity as a function of position for the 7.5-meter dash (red), the 15-meter dash (green), the 30-meter dash (yellow) and the 60-meter dash (blue). The colored curves with 95% confidence intervals represent the fitted velocity profiles. It can be seen that the velocity profiles of all four groups are comparable. Especially over the first couple of meters, hardly any differences can be observed in the evolution of running speed. Yet, at around 4 meters a small but marked divergence can be observed. While the velocity profiles for the 15-meter dash, the 30-meter dash and the 60-meter increase continuously throughout the first

7.5 meters of the trial, the velocity profile for the 7.5-meter dash starts to level off at around four meters towards reaching the finish line.

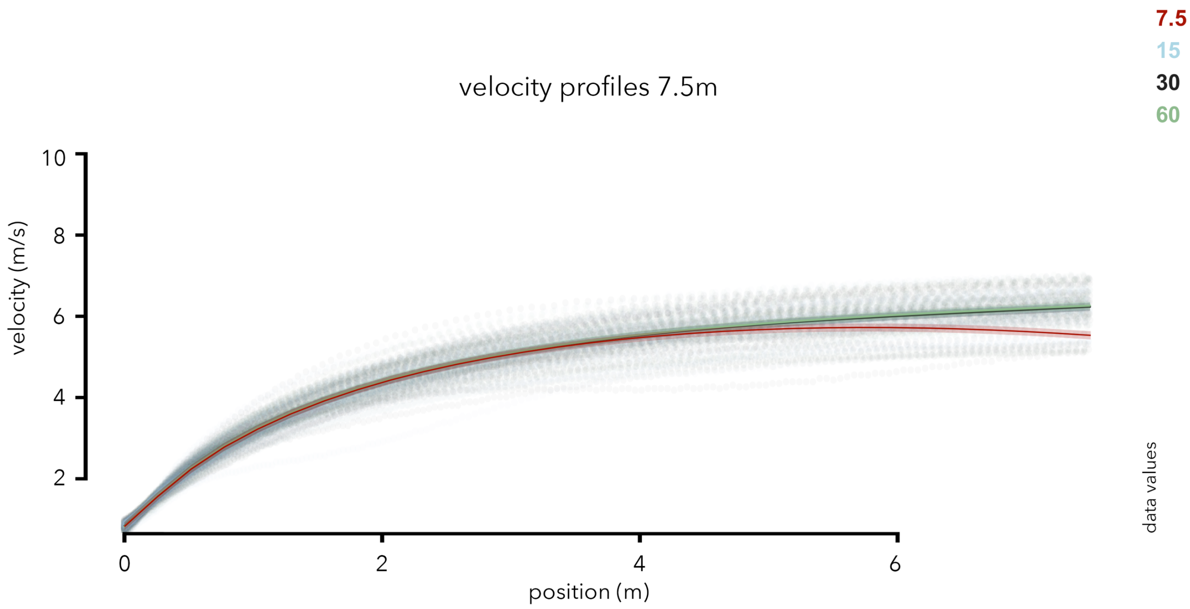

Figure 2. Velocity profiles over the first 7.5 meter for sprints with different target distances: 7.5-meter dash (red), 15-meter dash (green), 30-meter dash (yellow) and 60-meter dash (blue). Dotted curves represent measured running speed for different target distances, while unbroken curves, with 95% confidence intervals, represent fitted values. Generalized Additive Modeling was used to calculate the fitted values.

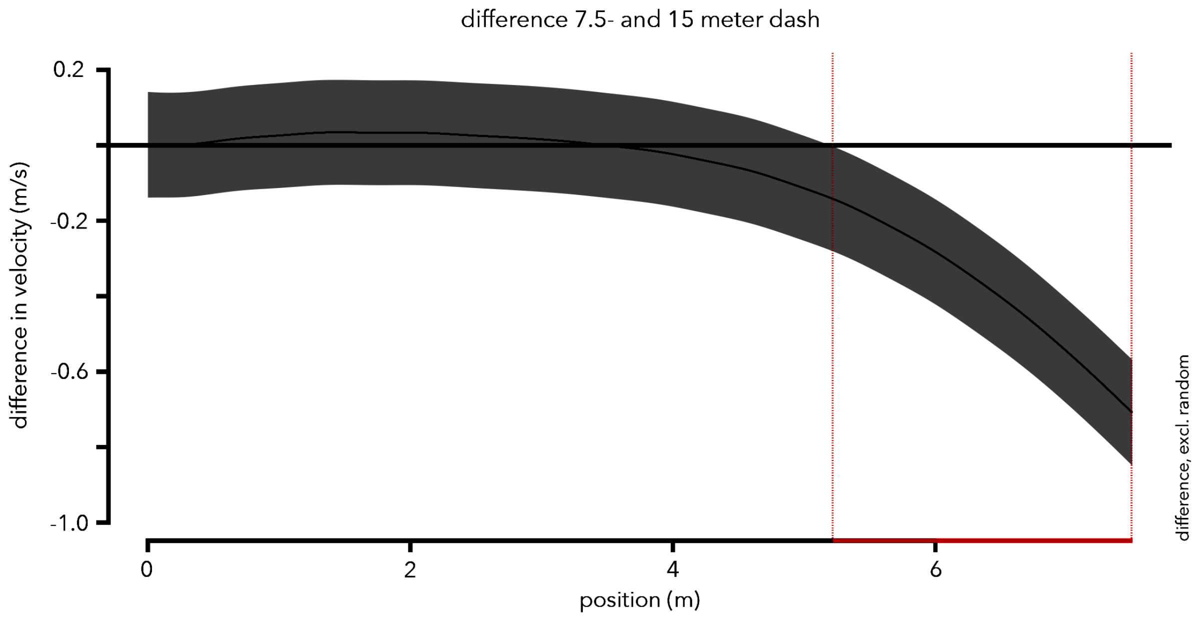

Figure 3. Difference curve for the velocity profiles of the 7.5-meter dash and the 15-meter dash. The average (curved line) and the 95% confidence interval (shaded region) are provided. Position (m) is on the abscissa and the estimated difference in velocity (m/s) is on the ordinate. The area demarcated by the red (dotted) lines represents the range of positions for which the difference between the velocity profiles (7.5-meter dash minus 15-meter dash) is significantly different from zero.

The apparent divergence between velocity profiles of the 7.5-meter dash and those of all other target distances can be more formally examined. On the basis of the fitted confidence intervals, velocity profiles of different target distances can be directly compared. *Figure 3* shows the difference curve for the velocity profiles of the 7.5-meter dash and the 15-meter dash. The red (dotted) lines represent the range of positions for which the difference between the two velocity profiles (7.5-meter dash minus the 15-meter dash) is significantly different from zero. Beyond 5.2 meters, the average running velocity for the 7.5-meter dash is significantly lower than for the 15-meter dash. The average difference increases up to about 0.8 ms^{-1} towards the end of the trial. Based on the fitted values in *Figure 2*, two other comparisons were made: The 7.5-meter dash versus the 30-meter dash and the 7.5-meter dash versus the 60-meter dash. Significant differences, comparable to those in *Figure 3*, were found for both. Their respective observed windows of significant difference were: 5.2-7.5 meters and 5.0-7.5 meters.

Above, we illustrated the Generalized Additive Modeling approach by only considering differences in running velocity over the first 7.5 meters of sprints with different target distances (i.e. 7.5, 15, 30 and 60 meters). Following the same rationale, we also checked for significant differences in running velocity over the first 15 meters of a 15-, 30- and 60-meter dash as well as significant differences in running velocity over the first 30 meters of a 30- and 60-meter dash. The results were highly similar to the case illustrated above: Running velocity decreased as participants closed in on the finish line. Results are displayed in *Appendix A*.

The fitted trajectories were obtained using the function *bam* of the *mgcv* package (Wood, 2003, 2004, 2011, 2017; Wood, Pya & Saefken, 2016). The command that was used to fit the Generalized Additive Model was[4]:

```
model = bam(Velocity ~    s(Position, by=TargetDistance, k=25) + TargetDistance +
                          s(TrialNumber) + PreviousTargetDistance +
                          s(Position, Participant_TargetDistance,
                          bs='fs', m=1), rho = 0.974)
```

The interpretation of this GAM specification is that running speed is predicted on the basis of a nonlinear pattern across position per target distance (using a maximum of 25 basis functions for nonlinear smoothing). We used position, instead of (the more intuitive measure of) time, to normalize running velocity across all trials and participants. After all, all participants were required to cover the same distances. Furthermore, the (nonlinear) effect of trial number on running velocity was incorporated to account for effects of fatigue. The effect of the previous target distance on running velocity was taken into account for the same reason. Finally, individual variation per target distance was taken into account by including factor smooths (`bs='fs'`) for the interaction term of participant and target distance. The term `m=1` indicates that the wigglyness for fitting individual curves is limited through a process of cross validation. This will avoid overfitting the data. Finally, *rho* is set to 0.974 to account for the great deal of auto correlation that is archetypical for time-series data. A full discussion of the results of all three fits (i.e. the 7.5-meter fit, the 15-meter fit and the 30-meter fit) of the GAMM would be beyond the scope of this paper. For now, it suffices to note that all effects, both fixed and random, were significant and that all models captured at least 99.4% of the variance. For a full overview of all model fits, please refer to *Supplementary Materials*. Having established that a nonlinear pattern exists for sprint running in a baseball context and that target distance

[4] Because of heteroscedasticity, we also fitted a more complex *gaussian location scale additive model* that is able to account for unequal variance in the data. Here, we will only report the simpler Generalized Additive Model since the conclusions reached from using either model are the same.

is only of influence on participants' velocity profiles near the finish line, we will now attempt to characterize this non-linear relationship, using participants' (maximum) running velocity and -acceleration as key variables.

A new macroscopic model on the kinematics of sprint running

Here, we will take a closer look at participants' velocity-acceleration profiles to characterize the nonlinear patterns observed. When considering the normalized velocity-acceleration profiles from *Figure 1*, a distinct pattern can be observed that is consistent over target distance. Right from the start of a sprint, acceleration increases rapidly as a function of running speed. This increase in acceleration persists until peak-acceleration is reached, which occurs on average when participants are at 36% (*SD* = 3.2%) of their maximal running speed. Interestingly, this figure is almost exactly the same for sprinting backwards (*M* = 36%; *SD* = 4.5%). When running speed is increased further, to about 80% of maximal running speed, acceleration declines in a fashion that seemingly mirrors the initial part of the sprint. This appears to be the case for all target distances. For target distances that allow participants to reach running velocities greater than 80% of their maximum, especially the 30-meter dash and the 60-meter dash, another distinct characteristic can be observed from participants' kinematic profiles. After having reached the 80%-mark, velocity-acceleration profiles become more irregular. As running speed increases from the 80%-mark, participants' acceleration remains slightly but mostly positive until maximal running velocity is reached (e.g. *Figure 1C–D*). When participants are close to running at their maximal capacity, acceleration oscillates to a greater or lesser degree around zero, in turn causing fluctuations in running velocity as well. This can be observed especially well from *Figure 1D* at around a normalized running velocity of 1. Finally, the 'finish-line effect' (i.e. the robust effect of participants slowing down near the finish-line) identified above, can be seen from panels *A* to *D* from *Figure 1* from participants' acceleration profiles becoming negative towards 'the end'. Over the next couple of paragraphs, we will attempt to characterize the relationship between running speed and -acceleration more formally.

A convenient and intuitive way to characterize the patterns observed in *Figure 1* would be with the use of polynomials. Typically, polynomials are computationally lightweight and have a simple form. Especially this latter trait is advantageous in the present context. *Equation 4* provides a formulation for a family of functions that can be used to approximate acceleration ($\ddot{x}$) as a function of running velocity ($\dot{x}$) in maximal-effort sprint running (see also *Figure 4*).

$$\ddot{x} = a(\dot{x} + c)^{n-2} \cdot (\dot{x} - \dot{x}_{max})^2 \rightarrow \{\dot{x} \mid 0 \leq \dot{x} \leq \dot{x}_{max}\};\ a > 0;\ c > 0;\ n > 2 \tag{4}$$

Where a and c are constants, n is the total degree of the polynomial and $\dot{x}_{max}$ is the maximal running speed that an athlete can achieve. Changes in constant c cause horizontal stretching relative to point $\dot{x} = \dot{x}_{max}$, whereas changes in n cause a change in shape of the polynomial function (see also: *Figure 4*). Finally, the a-parameter is used to constrain the polynomial so that acceleration ($\ddot{x}$) is never greater than an athlete's maximal acceleration ($\ddot{x}_{max}$). Please note that a is not a 'free parameter' since it is a function of $\dot{x}_{max}$, $\ddot{x}_{max}$, n and c (see also *Appendix B*).

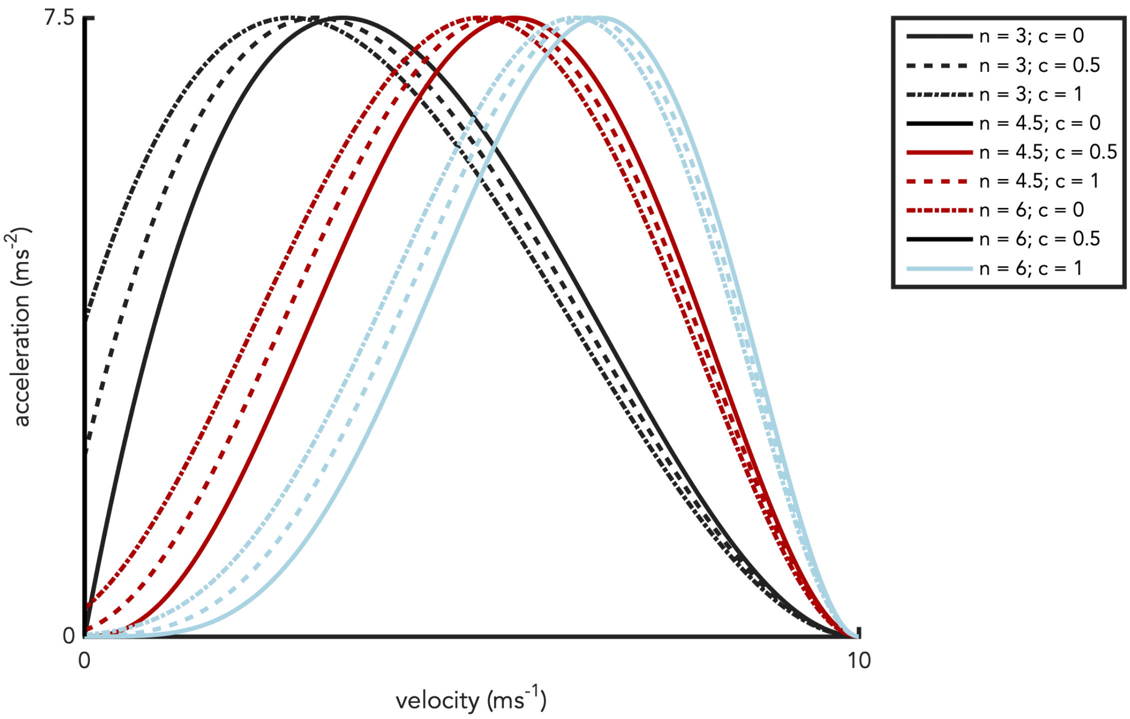

Figure 4. Exemplary plot showing polynomials of the form specified by *Equation 4*. The polynomial functions displayed here differ in order ($\boldsymbol{n}$) and in constant ($\boldsymbol{c}$). In this example, the $\boldsymbol{a}$-parameter was calculated, for every combination of $\boldsymbol{n}$ and $\boldsymbol{c}$, to keep maximal running velocity ($\dot{\boldsymbol{x}}_{\boldsymbol{max}}$) and maximal running acceleration ($\ddot{\boldsymbol{x}}_{\boldsymbol{max}}$) constant at 10$\boldsymbol{ms}^{-1}$ and 7.5 $\boldsymbol{ms}^{-2}$ respectively.

To model the kinematics of sprint running we focused on sprinting forwards (i.e. data from the *forward-condition*) and on sprinting backwards (i.e. data from the *backward-condition*). An optimization procedure was performed to find the optimal values for n and c. The total degree of the polynomial (n) was systematically varied between 2 and 10 with a step size of 0.1 and the horizontal stretch factor (c) was systematically varied between 0 and 100% of maximal running speed with a step size of 1%. Participants' maximal running speed ($\dot{x}_{max}$) and -acceleration ($\ddot{x}_{max}$) were determined from the data. Finally, the a-parameter could be established for every combination of n and c from variables: n, c, $\dot{x}_{max}$ and $\ddot{x}_{max}$ (see also: *Appendix B*). The optimization procedure was executed separately for trials of the forward-condition and for trials of the backward-condition. For every trial of every participant the coefficient of determination (R^2) was calculated. R^2's were then averaged over all trials of all participants to obtain an average coefficient of determination for every combination of n and c. This procedure was set up so as to identify the best combination for n and c in terms of R^2.

It was found, that a number of different combinations of n and c performed equally well (this was the case for both conditions). This was caused by an interdependence between n and c: An increase in n caused the apex of the polynomial to shift rightward, whereas an increase in c caused the apex of the polynomial to shift leftward. Thus, the effects of n and c may cancel each other out when it comes to fitting the local maximum in the data. To illustrate this effect, the best fits for data from the 30-meter dash of the forward-condition are displayed (*Figure 5*). The polynomial fits plotted in *Figure 5* vary widely in both n and c but exhibit an almost identical goodness-of-fit to the data ($R^2 = 0.90; SD = 9.0 \cdot 10^{-4}$). Thus, solely based on the coefficient of determination, no principled decision could be made in selecting one combination of n and c over another. However, goodness-of-fit should always be considered in light of parsimony. Ceteris paribus, simpler models are favored over more complex models. To characterize the tradeoff between goodness-of-fit and model complexity, information criteria like Akaike's Information Criterion (AIC) can be used. Akaike's Information Criterion rewards goodness-of-fit but penalizes model complexity as measured by the number of free parameters. In the present case, there was one particular combination for n and c (for both conditions) that stood out when taking model complexity into account: $n = 3.2$, $c = 0$. For this combination, the effect for one of the two free parameters (c) is cancelled, thus effectively reducing the number of free parameters by half without loss of explanatory power. Based on this observation, we select $n = 3.2$ and $c = 0$ to model the dynamics of sprint running, which simplifies *Equation 4* to hold:

$$\ddot{x} = a\dot{x}^{1.2} \cdot (\dot{x} - \dot{x}_{max})^2 \rightarrow \{\dot{x} \mid 0 \leq \dot{x} \leq \dot{x}_{max}\};\ a > 0 \qquad (5)$$

Using *Equation 5* to model acceleration in sprint running, the average coefficient of determination for trials of the forward-condition and for trials of the backward-condition was found to be 0.92 and 0.91, respectively.

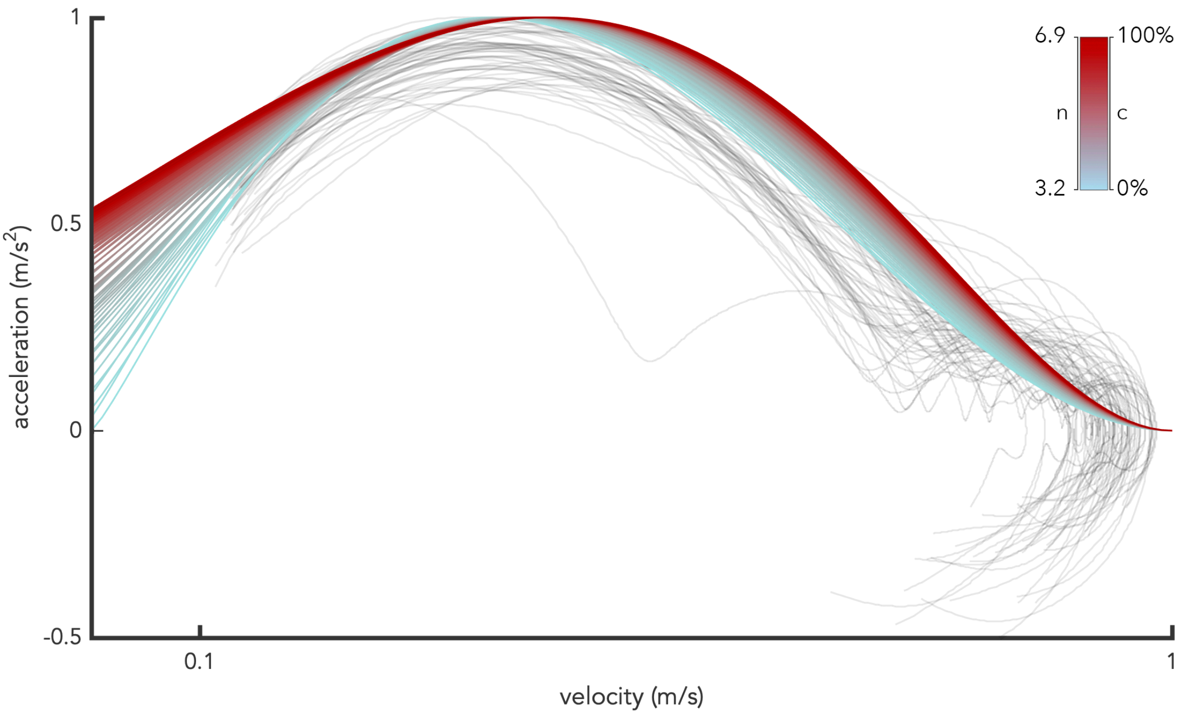

Figure 5. Best performing model specifications in terms of R^2 for all trials of all participants on the 30-meter dash of the forward-condition, with running velocity on the abscissa and running acceleration on the ordinate. Both running velocity and -acceleration have been normalized by scaling all values to participants' maximal running velocity and -acceleration, respectively. Semitransparent black lines represent participants' data, colored lines represent different model specifications (i.e. different values for $\boldsymbol{n}$ and $\boldsymbol{c}$). A blue-red gradient is used to represent different model specifications; the blue side of the spectrum specifies low values for $\boldsymbol{n}$ and $\boldsymbol{c}$ (from: $\boldsymbol{n = 3.2}$ and $\boldsymbol{c = 0}$) and the red side of the spectrum specifies higher values for $\boldsymbol{n}$ and $\boldsymbol{c}$ (up to: $\boldsymbol{n = 6.9}$ and $\boldsymbol{c = 100}$%).

Table 1. *Model goodness of fit (R^2) for position, velocity and acceleration for different target distances and running directions*

	Target Distance							
	Forwards				Backwards			
	7.5m	15m	30m	60m	3.75m	7.5m	15m	30m
Position	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Velocity	0.98	0.99	0.98	0.95	0.98	0.98	0.97	0.95
Acceleration	0.93	0.94	0.90	0.91	0.94	0.94	0.89	0.87

Next, we set out to validate *Equation 5* ($n = 3.2$). Preliminary inspection of the fits between the model and the data showed to be very promising. *Figure 6* shows a representative trial for one participant performing a 30-meter dash in the forward-condition. The model closely approximates position (*Figure 6A*), velocity (*Figure 6B*) and acceleration (*Figure 6C*) over time. This close fit between the model and the data was further confirmed by calculating the coefficient of determination for all trials of the forward- and backward-condition. Table 1 lists the average R^2-scores for position, velocity and acceleration, split out by target distance, for the forward-condition and the backward-condition. It can be seen that the model provides a very good description of the various kinematic measures that are related to performing a maximal-effort sprint. R^2-scores are even close to perfect for the distance-over-time relationship. When considering the average error in distance over time, for trials of the forward- and the backward-condition, it is found that the model is never off by more than 5.0% of the target distance both for the forward-condition as for the backward-condition. For the 60-meter dash of the forward-condition, the model is even accurate within 1%, meaning that the model is never off by more than 37cm).

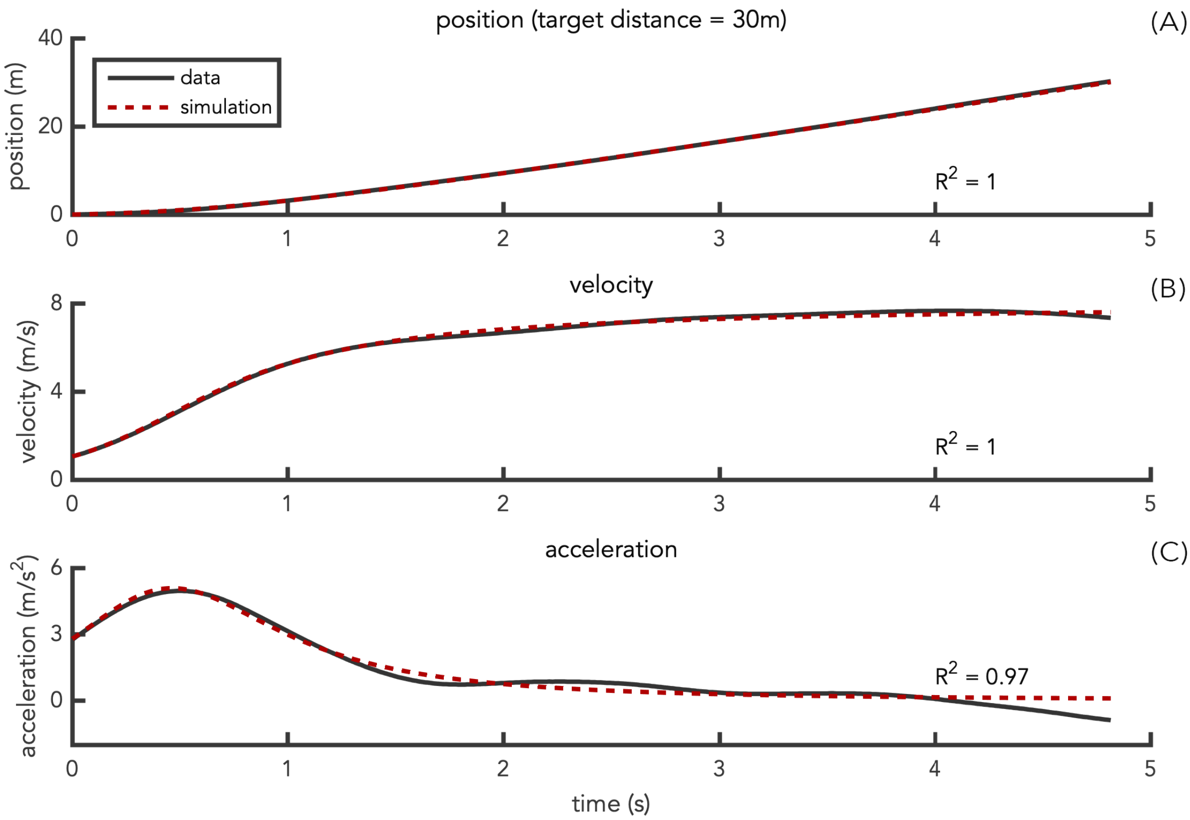

Figure 6. Time series data of position (A), velocity (B) and acceleration (C) for one representative trial (forward-condition, 30-meter dash). The solid blue lines represent the data and the red dashed lines represent the model's simulation.

The effect of turning on sprint performance

The final part of the results section concerns differences in sprint times for the *backwards-condition* and the *compulsory turn-condition*. When an outfielder is running to catch a ball that will fly overhead, two distinct locomotor strategies are typically observed. Either, the fielder is simply running backwards or the fielder turns to run to the designated location while looking over the shoulder to keep an eye on the ball. Paired-samples t-tests were used to compare sprint durations for each of the target distances of the backwards-condition with the compulsory turn-condition. There was a significant difference in sprint-duration on all target distances. Sprint duration was significantly shorter in the compulsory turn-condition as compared to the backwards-condition for the 3.75-meter dash [$t_{(30)}$ = -14.6, p < 0.001, d_s = -3.71], for the 7.5-meter dash [$t_{(30)}$ = -23.5, p < 0.001, d_s = -5.96], for the 15-meter dash [$t_{(30)}$ = -24.4, p < 0.001, d_s = -6.20] and for the 30-meter dash [$t_{(30)}$ = -23.0, p < 0.001, d_s = -5.85]. Close inspection of the data learned that this effect was very robust, only on one occasion did one participant perform the 3.75-meter dash faster in the backward-condition than in the turn-condition. *Figure 7A* represents the difference in sprint times as a function of target distance. It can be seen that the difference in sprint time increases almost linearly with increasing target distance. Thus, regardless of the distance that needs to be covered, it seems fastest to make a turn in running to make a catch.

Clearly, sprint times were markedly shorter in the compulsory turn-condition as compared to the backwards-condition, the question is: Did participants adhere to the fastest locomotor strategy when given freedom of choice? In the fourth condition, the *optional-turn condition*, participants were allowed to use either strategy (i.e. running backwards or turning) but were empathically instructed to get to the finish line as fast as possible. For every trial on every target distance in the fourth condition, we scored whether participants made a turn or not. When considering turning rate as a function of target distance (*Figure 7B*), we find that turning rates increase rapidly over the first three target distances to ultimately converge to about 100% for the last target distance. Thus, an increase in target distance, or analogously an increase in difference in sprint duration, is accompanied by an increase in turning rate. The target distance for which half of our participants would have turned appears to be at around a target distance of 5 meters.

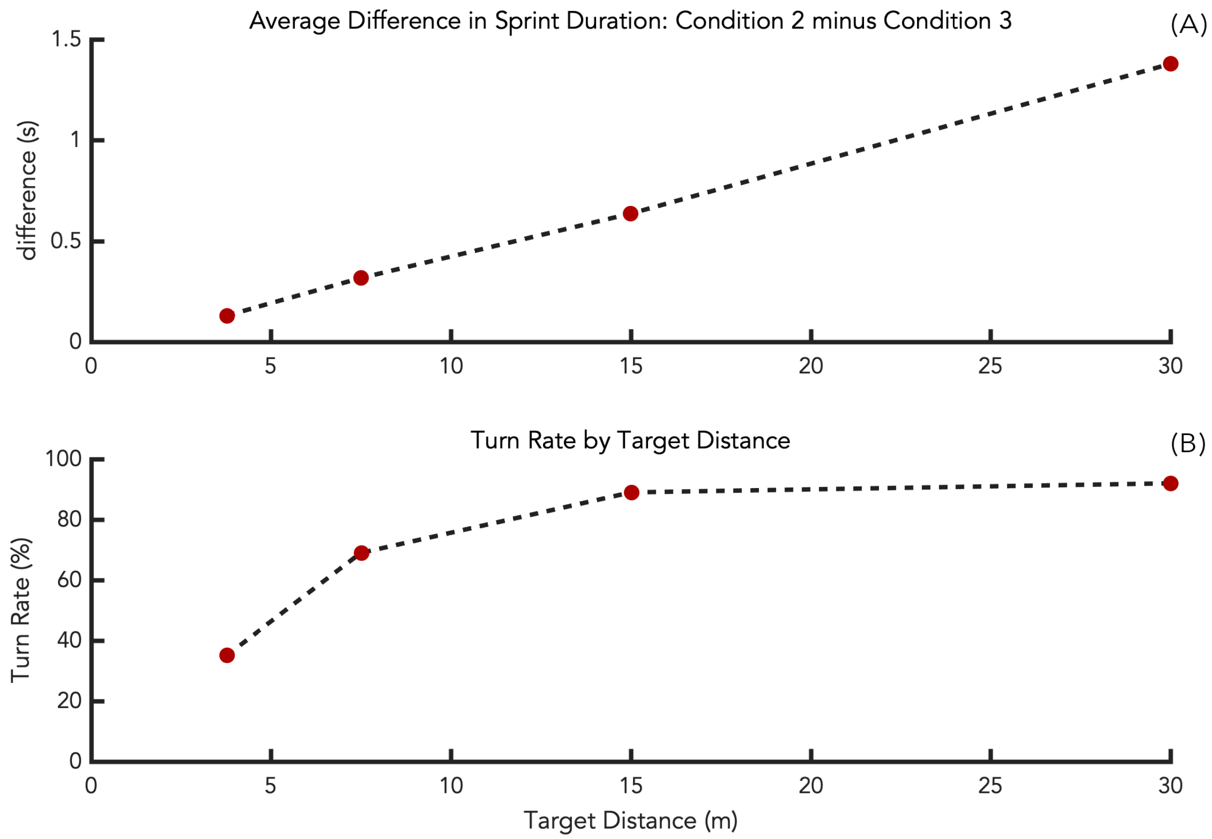

Figure 7. Average difference in sprint duration between the backwards-condition and the turn-condition (condition 3 minus condition 2) as a function of target distance (A) and turn rate by target distance (B).

DISCUSSION

The present contribution considered maximal-effort sprint running, in the context of catching fly balls, to determine the locomotor boundary that would separate catchable from uncatchable fly balls in an attempted catch. The overarching aim of this endeavor is to formalize an affordance-based control account for running to catch fly balls (cf. Fajen, 2007); one that is appreciative of the fact that locomotor behavior can be directly influenced by the perceived catchability of a ball. To that end, participants were required to complete a number of maximal-effort sprints of varying target distance, either running forwards or running backwards (in different variations). Using a Local Positioning Measurement system, participants' position over time was tracked. This allowed for a thorough analysis of the kinematic factors that limit the farthest distance that an athlete is able to cover over time. One of the main findings was that, contrary to what would be predicted from the context of athletic sprinting (e.g. Furusawa et al., 1927; Hill, 1927), the relationship between running speed and -acceleration in a maximal-effort sprint was not linear. For the present study, in which the conditions for sprinting were tailored to the baseball context, nonlinear speed-acceleration profiles were found that were best characterized by a 3.2-degree polynomial function (*Equation 5*). One of the key characteristics of this polynomial function is that it can be tailored to fit participants' locomotor abilities by simply plugging their maximal running speed and -acceleration. With this macroscopic dynamic model of sprint running, we were able to capture participants' acceleration profiles with an average R^2 of 0.92, position could even be described almost perfectly with R^2's close to 1. As R^2-values deviated little over target distance, it seemed fair to assume that participants exhibited no different pacing strategies for different target distances. This assumption was confirmed by performing regression analysis on participants' velocity profiles. Participants' velocity profiles proofed to differ only over target distance when they were close to reaching the finish line. For the 7.5-meter dash for instance, participants showed to slow down around the 5-meter mark, relative to the other target distances. That is to say, participants covered the first 7.5 meters of the 15-, 30-, and 60-meter dash slightly faster than the first 7.5 meters of the 7.5-meter dash. This was due to an effect we referred to as the 'finish-line effect'. This effect was observed for all target distances. Another finding of the present study pertained to the use of different running strategies for fly balls that are headed to the field behind the back of an outfielder. We found that an outfielder would always be better off making a turn to run to a location that is behind his or her back. Regardless of target distance, participants that were required to make a turn directly at the start of a trial were faster than participants that were required to cover that same distance simply running backwards. This was even the case for the nearest target distance (i.e. 3.75 meters). Interestingly though, participants did not naturally resort to the faster strategy. For the nearest target distance, participants even preferred running backwards over making a turn. Taken together, the present findings uncover some important pieces of the puzzle in quantifying the affordance for catchability. With the model presented here (valid both for forward- and backward sprinting) all pieces are in play to characterize and quantify the affordance of catchability in running to catch fly balls.

The affordance of catchability is presumed to have a profound effect on locomotor control and strategic gameplay in baseball (Fajen, 2005b, 2007). Consider for instance a scenario in which a fly ball is headed towards the far outfield, after being hit by the batter. This situation presents the fielding team with an opportunity to get ahead on the opposing team by making a catch. In this scenario, the infielders will probably recognize that the fly ball is not theirs to intercept and leave it to their outfielder-teammates to make the catch. Which in turn, allows the infielders to (re)position themselves strategically for when the ball returns to the infield. Considered as such, the affordance of catchability can have a direct influence on strategic gameplay. Another, more subtle, effect of perceived catchability on locomotor control might be observed from an outfielder running to catch a fly ball that is only just catchable. When running to catch a ball that is only just catchable, the outfielder might want to create a safe margin to account for any unexpected deviations in the ball's trajectory, this keeps the outfielder from having to increase running speed beyond his or her maximal running speed. In a series of papers, Fajen showed such anticipatory behaviors to be present in the case of braking a car to a safe stop (Fajen, 2005c, 2005a, 2005b, 2007). He showed that motorists would shy away from having to use the maximal rate of deceleration afforded by the brake of the car to come to a safe stop, presumably to account for any unexpected events that might occur while braking (Fajen, 2005a, 2007). So, much like the affordance of braking appears to be relevant for adequate braking behavior, the affordance of catchability seems to be relevant for locomotor control in running to catch fly balls.

Action boundaries in affordance-based control

The concept of affordance-based control was developed by Fajen to take account of the influence of the affordance of braking in braking behavior (Fajen, 2005c, 2005a, 2005b, 2007). Fajen proposed that braking is controlled by attending to the ratio of ideal deceleration (i.e.

the rate of deceleration that would bring the car to a safe stop without having to make any further braking adjustments) and maximal deceleration (i.e. the maximal rate of deceleration that can be achieved by braking maximally). Whenever the ratio of ideal deceleration (d_{ideal}) over maximal deceleration (d_{max}) is smaller than one, braking is afforded: The rate of deceleration required to come to a safe stop is smaller than the maximal rate of deceleration of the car. Conversely, whenever the ratio of ideal deceleration over maximal deceleration is greater than one, braking is no longer afforded: The rate of deceleration required to come to a safe stop is greater than the maximal rate of deceleration. Thus, control of braking, according to the concept of affordance-based control, boils down to braking such that the ratio of d_{ideal} and d_{max} remains smaller than one. By means of the present study, we strive to formulate a similar rational for the fly ball paradigm. Crucial to the formalization of affordance-based control in running to catch fly balls is the characterization of the affordance of catchability: What factors render a fly ball to be catchable?

The affordance of catchability has been examined in previous research concerning the relevance of action in perceiving the affordance of catchability (Fajen et al., 2011; Oudejans et al., 1996). It was found that the boundary between catchable and uncatchable fly balls was best described, either by the average velocity needed for successful interception (i.e. required velocity) or by the average acceleration needed for successful interception (i.e. required acceleration). Both required velocity and required acceleration performed better in characterizing the boundary between catchable and uncatchable fly balls than distance per se (Oudejans et al., 1996). There was however, not enough evidence to uniquely relate either required velocity or required acceleration to the affordance of catchability. In their study, Fajen and colleagues proposed an alternative measure to characterize the boundary between catchable- and uncatchable fly balls (i.e. time to spare). This measure was based off of the greatest distance that participants had covered at any time during the experiment while attempting to catch virtual balls. However, as this 'time to spare' measure yielded no different results with respect to their research question, its merits with respect to the affordance of catchability were not further investigated. Thus, the kinematic quality that unequivocally captured the boundary between catchable and uncatchable fly balls remained undisclosed. Finally, Postma and colleagues (2018) designed an experiment explicitly aimed at scrutinizing the boundary between catchable and uncatchable fly balls. Besides the usual suspects (i.e. required velocity and required acceleration) they also examined the greatest distance that participants had been able to cover in any of the trials during the experiment (i.e. locomotor range) for characterizing the boundary between catchable and uncatchable fly balls. It was found that this measure performed better than either required velocity or required acceleration. In fact, locomotor range captured more variance than the linear combination of running speed and -acceleration, suggesting that the boundary between catchable and uncatchable fly balls is probably best characterized by a nonlinear combination of running speed and -acceleration. However, since flight time was approximately the same over all trials in the experiment of Postma et al., the findings could not easily be generalized. Still, participants' maximal running speed and -acceleration, in relation to the farthest distance coverable over time, seemed to play a role in defining the boundary between catchable and uncatchable fly balls. Thus, to be able to formalize an affordance-based control account on locomotor control in running to catch fly balls, the relationship among maximum velocity, maximum acceleration and the distance coverable over time had to be established first.

The dynamics of athletic sprint running

In the context of athletic sprinting, Hill and colleagues (Furusawa et al., 1927; Hill, 1927) readily developed a macroscopic model on the dynamics of sprint running early on in the previous century. Ever since, their model has proven to be fruitful in characterizing the dynamics of running. Thus, a first step on our part was to examine whether the mono-exponential function, proposed by Hill (*Equation 1*), would also capture the dynamics of sprint running in a setting that resembled the baseball context. Therefore, we had participants perform a number of sprints with varying target distances, typical for the baseball context. We recorded participants' position over time and reconstructed their velocity and -acceleration profiles. Based on Hill's model (*Equations 1 and 3*), an inverse linear relationship between running speed and -acceleration was to be expected, instead a markedly nonlinear pattern was observed (see also *Figure 1*). From Hill's model on athletic sprinting, athletes are predicted to reach peak-acceleration straight away, which makes sense when one considers that track-and-field athletes assume a specific position (perhaps using starting blocks) to prepare for an optimal start. Such an ideal start however, might not be realistic for the case of running to intercept a baseball. In baseball, outfielders are clueless about where the ball will be heading right until it leaves the bat. As such, outfielders need to assume a position that allows them to move quickly in any direction. So, even without the starting blocks, outfielders might not reach peak-acceleration as fast as athletic-sprinters would. This is exactly what we observed in our data. We found a markedly nonlinear pattern between running speed and -acceleration. The observed kinematic patterns deviated significantly from the linear trend predicted from Hill's model. This deviation from linearity is tangible especially for lower running speeds at the start of a sprint. Outfielders rarely cover more than 30 meters while running to make a catch. Therefore, it is specifically crucial to model the initial phase of the sprint right. Therefore, we set out to develop a model to characterize the kinematics of sprint running especially for the context of running to catch a baseball.

The kinematics of sprint running in baseball

Based on data from our experiment, we derived a 3.2-degree polynomial function (*Equations 4-5*) that captured the kinematics of sprint running in a baseball setting very well. With *Equation 5* we were able to capture over 90% of the variance in participants' acceleration profiles (both for trials of the forwards-condition as for trials of the backward-condition). Integrating over time, predictions of participants' position over time were even close to perfect, with R^2-values converging to 1.0. The model was never off by more than 5% of the distance that had actually been covered at time t. This renders the model very useful for characterizing the farthest distance that an outfielder in baseball would be able to cover over time and thus, by proxy, whether a fly ball is either catchable or uncatchable. Ultimately, this allows for the quantification of the effects of the affordance of catchability on locomotor control and strategic gameplay, even when the distance to be covered is only short.

While the coefficient of determination was high across the board, target distance might have had a pronounced influence on how participants performed their sprints. It has often been observed that the duration of physical performance affects the way people spend their energy. Therefore, to validate *Equation 5*, we set out to examine the influence of target distance on the evolution of velocity profiles in sprinting. Overall, target distance was of no influence on the way participants performed their sprints. For the larger part, velocity profiles for different target distances were identical. We did however, find a 'finish-line effect'. Even though participants were empathically instructed to perform the sprints as fast as possible, participants typically slowed down a couple of meters before reaching the finish line. This effect was found to be very consistent and affected performance over all target distances. This indicates that it is not an effect of fatigue but that it is specifically linked to approaching the finish line. It seems unlikely however that this finish line effect is observed in the case of running to catch a fly ball. It would make little sense for an outfielder to slow down in the final stages of the attempted catch. As such, we feel that *Equation 5* might be utilized to predict catchability, regardless of the distance that an outfielder might need to cover.

With the model presented here (*Equations 4–5*), we do not intend to present a dynamical model for maximal-effort sprinting. In fact, using the model as a dynamical model for sprint running would be problematic as the origin of the function lies at: ($\dot{x} = 0, \ddot{x} = 0$). When used as a dynamical model, the virtual agent would never get moving when starting from standstill. This methodological difficulty might be easily circumvented by adding an attractor-variable (e.g. the finish-line) that 'pulls' the virtual agent out of its saddle-point into the sprint. Another option would be to up the total degree of the function (n) and include an appropriate constant (c), this would alter the shape of *Equation 4* such that when running velocity equals zero, acceleration is greater than zero (i.e.: $\dot{x} = 0$, $\ddot{x} > 0$). However, the present data did not provide enough information to warrant a principled decision of any combination of n and c over another. At low velocities, acceleration could not be measured very accurately using the LPM-system (Ogris et al., 2012; Stevens et al., 2014), also because the start of a trial was taken to be the instant participants reached a velocity threshold of 1 ms^{-1}, accelerations for running velocities lower than 1 ms^{-1} could not be obtained. Therefore, we applied Occam's Razor and went with the most parsimonious solution ($n = 3.2$, $c = 0$), see also the results section. For future research it would be well-advised to make use of force-plates to measure accelerations at the start of a sprint, or even at standstill. For present purposes however, the model presented here provides an apt and accurate description of the kinematics of maximal-effort sprint running for the baseball context.

Affordance-based control in running to catch fly balls

With the kinematic model on sprint running proposed in this study, the influence of the affordance of catchability on locomotor control and strategic gameplay can be quantified. To date, the affordance of catchability has resisted proper characterization. A number of studies have attempted to relate outfielders' locomotor abilities to the boundary between catchable and uncatchable fly balls (Fajen et al., 2011; Oudejans et al., 1996; Postma et al., 2018). In the latest state of play, it was suggested that the farthest distance coverable within a certain time (i.e. locomotor range) was one of the key determinants of catchability (Postma et al., 2018). However, it remained unclear how the farthest distance coverable over time could be properly characterized. In this study, we have unpacked 'locomotor range'. With the present findings, the affordance of catchability can now be determined at any moment in time. When an outfielders' current running speed ($\dot{x}$), maximal running speed ($\dot{x}_{max}$) and maximal running acceleration ($\ddot{x}_{max}$) are known, the remaining flight time of the ball can be used to calculate the maximal distance that the outfielder is able to cover, we will refer to this maximal distance as s_{max}. As such, an outfielders' s_{max} can be determined at any moment in time. Relating the value for s_{max} to the distance that the outfielder is still required to cover in order to make the catch (s_{req}), we obtain a ratio that specifies the catchability of a fly ball at any moment in time: $\frac{s_{req}}{s_{max}}$. With this ratio, the catchability of a fly ball over time is specified:

A fly ball is catchable for as long as the ratio of s_{req} over s_{max} is smaller than 1, conversely a fly ball is uncatchable whenever the ratio of s_{req} over s_{max} is greater than 1. Considered as such, it is interesting to note that a fly ball might be catchable at first (i.e. $\frac{s_{req}}{s_{max}} < 1$), but might become uncatchable later on (i.e. $\frac{s_{req}}{s_{max}} > 1$), for example when an outfielder gets a bad jump on the ball.

While the ratio of s_{req} over s_{max} provides a convenient methodological tool to determine catchability, it should not be taken to represent the affordance-based control principle, by which outfielders guide their locomotor behavior, just yet. The ratio of s_{req} over s_{max} is not unique to specify the affordance of catchability. The affordance of catchability might just as well be captured using a ratio of required velocity over maximal velocity $\left(\frac{v_{req}}{v_{max}}\right)$ or analogous required acceleration over maximal acceleration $\left(\frac{a_{req}}{a_{max}}\right)$. In fact, there are as many ways to define the affordance of catchability as there are kinematic quantities to measure an outfielder's locomotor abilities by. While there are, mathematically speaking, many different ways to specify the affordance of catchability, outfielders might not be able to directly perceive all of these. At present it is unclear whether outfielders are able to directly perceive the ratio of s_{req} over s_{max}. So clearly, a next step is needed to uncover the ratio by which the affordance of catchability is actually perceived (cf. Fajen, 2005c, 2005a, 2005b, 2007).

Although the present data provide no basis for selecting the appropriate kinematic ratio to specify the affordance of catchability by, an interesting candidate can be found in the ratio of required acceleration (a_{req}) over maximal acceleration (a_{max}). This particular ratio seems promising (if only from a conceptual point of view) because a_{req} and a_{max} are both accounted for in literature. In running to catch a fly ball, an outfielder's maximal acceleration can be characterized by *Equation 5* from the present contribution. Required acceleration, on the other hand, can be derived from a paper by Rozendaal and van Soest (2003). They showed that the acceleration that is required to successfully intercept a fly ball can be derived from the optics of the Optical Acceleration Cancellation (OAC) strategy. The OAC-strategy holds that an outfielder will arrive at the right place in the right time to make a catch if the rate of change of the optical position of the ball on an image plane (i.e. optical acceleration) can be successfully nulled (Chapman, 1968; Michaels & Oudejans, 1992). Assuming that the outfielder's eye remains at a constant level and setting optical acceleration to equal zero, required acceleration can be derived from the Optical Acceleration Cancellation strategy (Rozendaal & Van Soest, 2003). While the mere observation that both parts of the fraction can be grounded in theory is no reason to assume that outfielders would in fact rely on the ratio of a_{req} and a_{max}, it does allow for us to explore the merits of an affordance-based control theory that allows for the affordance of catchability to be perceived directly[5].

The ratio proposed above (a_{req} over a_{max}) to capture affordance-based control in running to catch fly balls, is in many respects similar to Fajen's original formalization of affordance-based control in braking (d_{req} over d_{max}). In both cases, behavior can be controlled by attending to

[5] Note that it is not necessary for an outfielder to directly perceive a_{max} per se. For affordance-based control to work, the outfielder needs only to directly perceive a_{req}; through calibration, information about required acceleration can be expressed in intrinsic units of maximal acceleration (Fajen, 2005c).

the ratio of some environmental demand over the matching action boundary. If the ratio is smaller than one, the intended action is afforded, if on the other hand the ratio is greater than one, the intended action is not afforded. Conceived as such, behavioral control is characterized in terms of possibility, rather than in terms of actuality (Harrison, Turvey, & Frank, 2016). Fajen's affordance-based control strategy for braking specifies the boundary conditions within which safe braking is afforded, however no control law is provided that takes account of how motorists *actually* decelerate to come to a safe stop. This renders it very difficult to predict the behavior that an agent will exhibit under certain circumstances. Interestingly, this is where the suggested ratio of a_{req} over a_{max} excels. With the ratio of a_{req} over a_{max} it is not only possible to specify the affordance of catchability, it is also possible to derive a control-law that specifies how an outfielder is expected to behave while running to catch a fly ball. This control-law lies concealed within the ratio itself: When $\frac{a_{req}}{a_{max}} = 0$, a_{req} must be 0, specifying that the outfielder is running at the constant velocity that would lead him or her to successfully intercept the fly ball. This special case much resembles the rationale of the OAC-strategy (i.e. optical acceleration equals zero for the constant running velocity that will lead an outfielder to the right place in the right time to intercept the ball). If the ratio of a_{req} over a_{max} would in fact be the ratio by which outfielders control their locomotor behavior, then that would align this theory with Chapman's original formulation of locomotor control in running to catch fly balls (Chapman, 1968). Many studies have illustrated the merits of the Chapman strategy in accounting for locomotor patterns in running to catch fly balls (Dienes & McLeod, 1993; Fink et al., 2009; McLeod & Dienes, 1996; Michaels & Oudejans, 1992). This would add to the existing literature with the added advantage of being able to account for locomotor behavior that is contingent on directly perceiving the affordance of catchability.

Conceptually, the ratio of a_{req} over a_{max} has undeniable merits. Yet, in its current concretization is seems not feasible for characterizing locomotor control in running to catch fly balls. As it stands, a_{max} is given by a differential equation of which the origin lies at: ($\dot{x} = 0$; $\ddot{x} = 0$), meaning that an outfielder's maximal acceleration equals zero at standstill. The implication of this is that practically every fly ball is perceived to be uncatchable at standstill. Anecdotally, this seems not realistic. While it might be the case that outfielders need to move first, before they can accurately perceive the catchability of a fly ball (cf. Oudejans et al., 1996), this is not a route we want to pursue. Like we mentioned earlier, the present experimental setup did not provide us with accurate measurements of acceleration at low running speeds, as such, in further research we want to explicitly test running acceleration right at the start of a sprint to reliably estimate maximal acceleration at standstill. In parallel, we set out to examine alternatives to the ratio of a_{req} over a_{max} to specify the affordance of catchability by. Still, conceptually, the ratio of a_{req} over a_{max} makes for a strong candidate for affordance-based control in running to catch fly balls.

Turning versus running backwards

Finally, we considered running behavior for situations in which an outfielder is confronted with a fly ball that is heading to the field behind his or her back. In such situations, outfielders often display one of two distinct running strategies: Either they simply run backwards, facing in the direction opposite to the line of travel or they make a swift turn, running forwards while looking over the shoulder. Even though the latter strategy seems to have an edge over the former in terms of biomechanics (typically, running forwards is faster than running backwards), outfielders do not uniquely resort to the turning-strategy when running to catch a fly ball that is bound to land behind their initial position. Apparently, there is an advantage to simply running backwards. To scrutinize the difference between the two locomotor strategies outlined above, we had participants perform three conditions related to sprinting backwards: the *backwards-condition*, the *compulsory-turn condition* and the *optional-turn condition*. A direct comparison between the backwards-condition and the compulsory-turn condition confirmed the presumed advantage of turning over not turning. Regardless of target distance, participants were always faster in the compulsory-turn condition than in the backwards-condition. Interestingly though, when participants were given freedom of choice in selecting either strategy to complete a sprint in the optional-turn condition they did not always resort to the (faster) turning-strategy. We found that participants predominantly covered the shortest target distance (i.e. 3.75 meter) without turning, while greater target distances were predominantly covered using the strategy from the compulsory turn-condition. In light of the fact that it is always faster to make a turn and that participants were empathically instructed to get to the finish line as fast as possible, this is somewhat surprising. For the shortest distance, it might be argued that the average difference in sprint time (i.e. 130ms) was not perceptible, making not turning the easier option in the face of doubt. This line of reasoning, however, makes less sense for greater target distances, such as the 30-meter dash, for which it would be on average 1.38 seconds faster to make a turn. Still on 8% of the trials, participants did not make a turn. We believe this is caused by participants that were unable to make a turn at high velocities. Some participants started out sprinting backwards, only realizing that it might be faster to make a turn after some while, after which backwards running speed was too high to make a coordinated turn. This however remains to be determined.

Conclusion

In conclusion, in the present contribution, we studied the dynamics of maximal-effort sprint running in the context of running to catch fly balls. The aim was to map the relation among a player's maximum velocity, maximum acceleration and the distance coverable within a certain time (e.g. the remaining flight time of a ball). First, we established that Hill's leading model on the dynamics of running in athletic sprinting was not directly transferable to the context of running to catch baseballs; a marked difference was observed between the dynamics of athletic sprinting and the dynamics exhibited by participants in the present study. This led us to propose an alternative model, specifically designed to capture the dynamics of sprinting in a baseball setting. With this model, we were able to make highly reliable predictions of participants' position-, velocity- and acceleration over time. Third, using Generalized Additive Modelling, we were able to establish that target distance was of no profound influence on the dynamics of sprint running, rendering our alternative model valid for different target distances up to 60 meters. Finally, it is interesting to note that for baseballs heading to the field behind an outfielder, it would always be faster for the outfielder in question to make a turn. Yet, when given freedom of choice, participants did not always adhere to the fastest strategy. Taken together, the present findings might help to quantify the effects of the affordance of catchability on locomotor control and strategic gameplay of outfielders. Quantification of this effect might in turn lead to the formulation of an affordance-based control strategy for running to catch fly balls specific and other interceptive behavior in general.

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APPENDIX A

Participants' running velocity declined towards the finish-line with an order of magnitude similar to the decline observed in *Figure 3*. With respect to differences in running velocity over the first 15 meters of the 15-, 30- and 60-meter dash, we found a significant window of difference (11.9 – 15 meters) for the comparison of the 15-meter dash with the 30-meter dash as well as a significant window of difference (11.6 – 15 meters) for the comparison of the 15-meter dash with the 60-meter dash. Leaving the comparison of running velocity over the first 30 meters of the 30-meter dash with the 60-meter dash. We found a significant window of difference of 25.9 to 30 meters. For all analyses presented here, alpha-inflation was corrected for using a Bonferroni-correction.

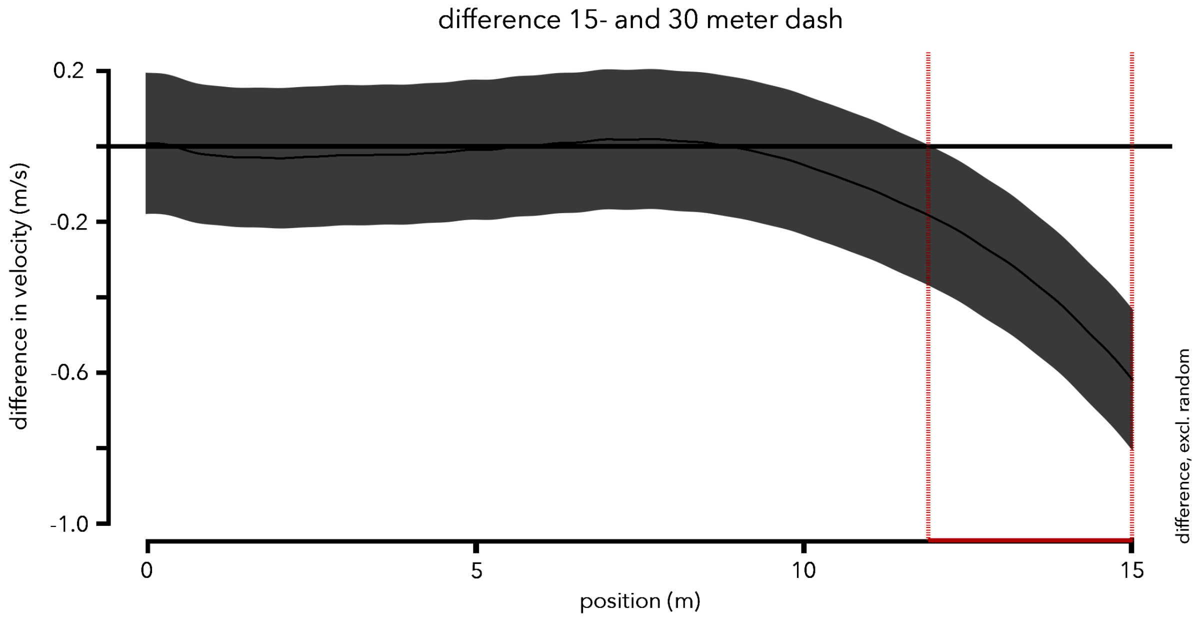

Figure A.1. Difference curve for the velocity profiles of the 15-meter dash and the 30-meter dash. The average (curved line) and the 95% confidence interval (shaded region) are provided. Position (m) is on the abscissa and the estimated difference in velocity (m/s) is on the ordinate. The area demarcated by the red (dotted) lines represents the range of positions for which the difference between the velocity profiles (15-meter dash minus 30-meter dash) is significantly different from zero.

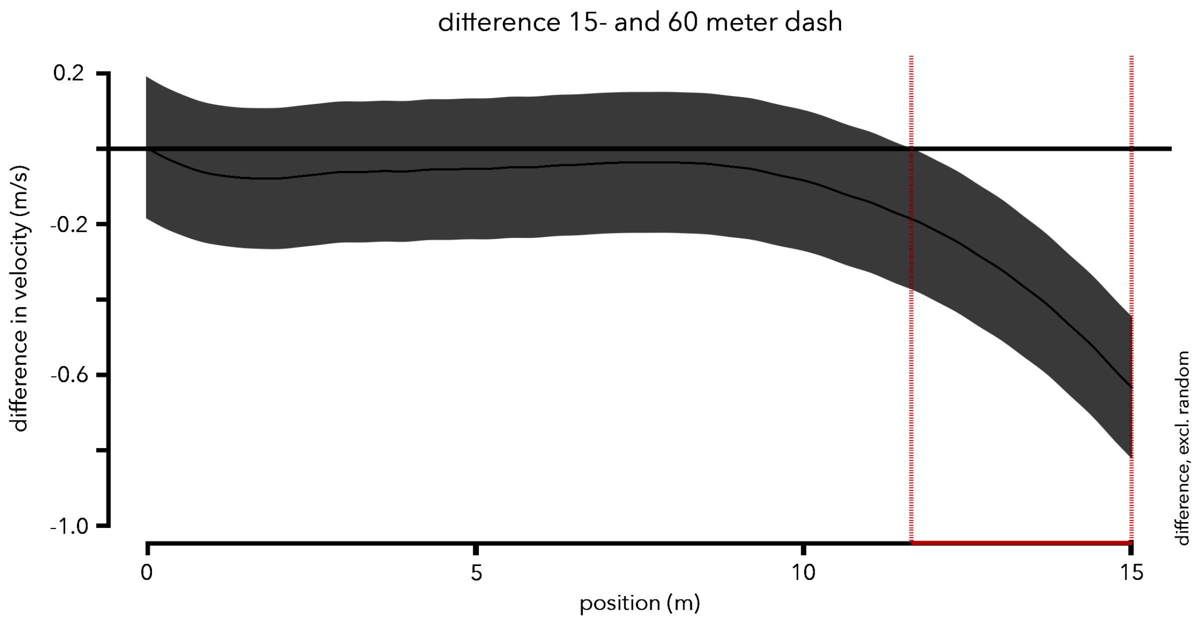

Figure A.2. Difference curve for the velocity profiles of the 15-meter dash and the 60-meter dash. The average (curved line) and the 95% confidence interval (shaded region) are provided. Position (m) is on the abscissa and the estimated difference in velocity (m/s) is on the ordinate. The area demarcated by the red (dotted) lines represents the range of positions for which the difference between the velocity profiles (15-meter dash minus 60-meter dash) is significantly different from zero.

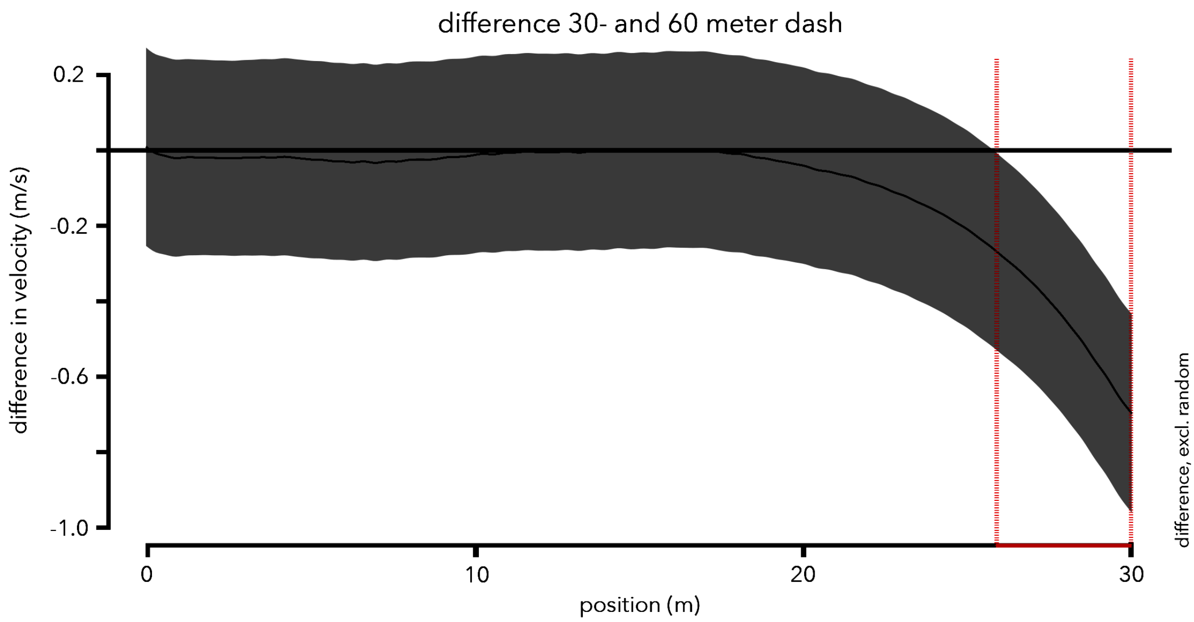

Figure A.3. Difference curve for the velocity profiles of the 30-meter dash and the 60-meter dash. The average (curved line) and the 95% confidence interval (shaded region) are provided. Position (m) is on the abscissa and the estimated difference in velocity (m/s) is on the ordinate. The area demarcated by the red (dotted) lines represents the range of positions for which the difference between the velocity profiles (30-meter dash minus 60-meter dash) is significantly different from zero.

APPENDIX B

The a-parameter can be derived by setting the first derivative of *Equation 4* to zero and solving for $\dot{x}$, providing:

$$\dot{x} = \frac{(n-2)\,\dot{x}_{max} - 2c}{n} \tag{A.1}$$

Equation 6 provides the $\dot{x}$-coordinate for which $\ddot{x} = \ddot{x}_{max}$. Knowing the $\dot{x}$-coordinate for which $\ddot{x}$ is maximal allows for the a-parameter in *Equation 4* to be established. For $\ddot{x} = \ddot{x}_{max}$, the a-parameter is given by:

$$a = \frac{\ddot{x}_{max}}{\left(\frac{(n-2)\,\dot{x}_{max} - 2c}{n} + c\right)^{n-2}\left(\frac{(n-2)\,\dot{x}_{max} - 2c}{n} - \dot{x}_{max}\right)^{2}} \tag{A.2}$$

Subsequently plugging *Equation 2* into *Equation 1* provides:

$$\ddot{x} = \frac{\ddot{x}_{max}}{\left(\frac{(n-2)\,\dot{x}_{max} - 2c}{n} + c\right)^{n-2}\left(\frac{(n-2)\,\dot{x}_{max} - 2c}{n} - \dot{x}_{max}\right)^{2}}(\dot{x}+c)^{n-2}(\dot{x}-\dot{x}_{max})^{2} \tag{A.3}$$

Equation 7 is a reformulation of *Equation 4* in which the a-parameter is described in terms of: $\ddot{x}_{max}$, $\dot{x}_{max}$, n and c.

VI

GENERAL DISCUSSION

Dees B.W. Postma

Through a series of experiments, the present thesis set out to develop an affordance-based control strategy for running to catch fly balls. In doing so, this thesis builds on Fajen's seminal work on affordance-based control in the visual guidance of braking a car to a safe stop (Fajen, 2005c, 2005b, 2005a, 2007a). Affordances are thought to play a crucial role in (motor) behavior, not only in braking but in all human endeavors (Fajen, 2007a; Gibson, 1979; Harrison, Turvey, & Frank, 2016; Michaels & Carello, 1981; Turvey, Shaw, Reed, & Mace, 1981). The concept of affordance-based control strongly reflects this notion, highlighting the importance of affordances in control of visually guided action. To advance the framework of affordance-based control, the present thesis aimed to extend its principles to the fly ball paradigm.

INTRODUCTION

After providing a general introduction, this thesis started off by scrutinizing a crucial assumption foregoing the development of an affordance-based control strategy for running to catch fly balls, which pertained to outfielders' gaze behavior. From an affordance-based control perspective, outfielders are expected to maintain close-to-continuous visual contact with the ball to guide their locomotor behavior. While intermittent visual contact with the ball would not dismiss the potential use of an affordance-based control strategy, finding that outfielders maintain continuous visual contact with the ball would be fitting. Chapter 2 aimed to shed light on outfielders' gaze behavior while running to catch fly balls. Gaze behavior was studied by having participants run to intercept fly balls projected along their sagittal plane. Participants were equipped with an unobtrusive, mobile gaze tracker. During the experiment, participants were presented with fly balls projected either in front of- or behind their initial position. Also, fly balls could either be catchable or uncatchable. So far, gaze behavior had only been studied for outfielders running to intercept *catchable* fly balls (Oudejans, Michaels, Bakker, & Davids, 1999). The experiment that is detailed in Chapter 2 adds to this literature by extending the range to also include *uncatchable* fly balls. This is relevant for the development of an affordance-based control strategy for running to catch fly balls as the affordance of catchability might have a profound influence on locomotor control. In Chapter 2, it is thus examined whether outfielders maintain continuous visual contact with the ball while making an attempted catch for fly balls that could be either catchable or uncatchable. Analyses showed that participants continuously foveated the ball, regardless of the ball's trajectory, either catchable or uncatchable. Finding that participants maintained continuous visual contact with the ball was fitting for the potential use of an affordance-based control strategy, thus inviting further development on the concept.

While gaze behavior proved to be fitting, the informational specification underlying the continuous visual guidance of locomotor behavior remained elusive. What optical information could serve as the basis for affordance-based control in running to catch fly balls? The quest for informational specification ultimately led back to the Optical Acceleration Cancellation (OAC) strategy, the prominent account for characterizing locomotor behavior in running to catch fly balls (e.g. Chapman, 1968; Fink, Foo, & Warren, 2009; Kistemaker, Faber, & Beek, 2008; McLeod, Reed, & Dienes, 2001, 2006; Michaels & Oudejans, 1992; Todd, 1981; Zaal, Bongers, Pepping, & Bootsma, 2012; Zaal & Michaels, 2003). To check whether the OAC-strategy could be extended to also include the affordance aspects of running to catch fly balls, the use of optical acceleration cancellation in relation to judgments of catchability was examined in Chapter 3. The OAC-strategy holds that an outfielder would get to the right place in the right time to make a catch by running such that optical acceleration is successfully nulled. From this, it follows that optical acceleration cancellation might be informative of the affordance of catchability under two specific circumstances. First, a fly ball might be perceived *catchable* when an outfielder is running such that optical acceleration is successfully nulled. Second, a fly ball might be perceived *uncatchable* when optical acceleration is nonzero and running velocity cannot be further increased. Conceived as such, an outfielder's maximal running speed serves as a constraint on optical acceleration cancellation, thus informing about catchability. To examine whether judgments of catchability would fit the use of optical acceleration cancellation, an experiment was designed in which participants were required to indicate the catchability of fly balls. Participants were required to run to intercept fly balls, calling 'no' when perceiving a fly ball to be uncatchable. From the use of optical acceleration cancellation, it was expected that outfielders would only report a fly ball to be uncatchable while running at maximal velocity. This hypothesis was tested by examining participants' running speeds at the moment of calling 'no'. It was found however that participants were often far from running at their maximal velocity. From this, it could be concluded that optical acceleration cancellation, in unison with the constraint of maximal running velocity, is unlikely to give rise to the perception of the affordance of catchability. For the sake of thoroughness, participants' running accelerations were also examined at the moment of calling 'no': Perhaps participants' maximal running acceleration, rather than their maximal running velocity, served as the critical constraint on optical acceleration cancellation. This however, proved not to be the case either: Participants were often far from accelerating maximally at the moment of calling 'no'. Finally, it was examined whether participants had already reached maximal running speed or acceleration *before* having indicated that a fly ball was uncatchable. However, these results came out negative as well. Taken together, these findings do not support the notion that optical acceleration cancellation is the basis for perceiving the affordance of catchability. Thus, an alternative approach was needed to develop an affordance-based control strategy for running to catch fly balls.

As a first step in developing an affordance-based control strategy for running to catch fly balls, Chapter 4 set out to establish whether fielders are at all able to perceive the affordance of catchability. If fielders proved unable to accurately perceive the catchability of a fly ball, an affordance-based control strategy would not seem viable. It was found however, that participants were well able to judge the catchability of a fly ball. Participants were able to correctly classify over 85% of the fly balls that were projected towards them. Interestingly, participants hardly ever ran at maximal velocity while judging a fly ball to be uncatchable, which strengthens the findings from Chapter 3. Having established that the affordance for catchability could be reliably judged, Chapter 4 continues to determine what behaviorally relevant agent-environment factors relate to the affordance of catchability. It was found that the affordance of catchability could aptly be characterized on the basis of five such factors, capturing well over 80% of the variance in catching performance. One of these relevant factors was '*locomotor range*', which was taken to be the greatest distance that a participant was able to cover in any of the trials during the experiment. This variable is of particular interest as it is a reflection of an outfielder's locomotor abilities. However, since all fly balls from this experiment had approximately the same flight time, the measure of locomotor range was specific to that particular experimental context. This rendered extrapolation to the general case of catching fly balls difficult. Thus, an important question remained: What determines the locomotor range of an outfielder?
With the environment-side of the affordance of catchability charted, the agent-side (i.e. 'locomotor range') required further unpacking. What makes that an outfielder in baseball is unable to catch one fly ball, but is perfectly able to catch another? This question is crucial to the present inquiry into affordance-based control as it concerns the factors that limit what an outfielder can and cannot do. Being able to complement the (well-charted) environment-side of the affordance of catchability with a precise characterization of the agent-side would provide a valuable opportunity for the formalization of affordance-based control for running to catch fly balls. This provided the rationale for Chapter 5.

Chapter 5 showed that the action boundary of an athlete, performing maximal sprints on AstroTurf, could be characterized as a function of an athlete's current running speed, maximal running speed and maximal running acceleration. By modelling maximal running acceleration as a polynomial function of the aforementioned factors, over 90% of the variation in participants' acceleration profiles could be accounted for. This polynomial relationship proved to be robust over different target distances up to 60 meters, which is about the maximal distance that an outfielder in baseball would need to cover in order to make a catch in baseball. Furthermore, the identified polynomial relationship proved to be valid for sprinting backwards as well. Simply scaling the model-parameters to match participants' maximal backwards running speed and -acceleration also rendered it valid for characterizing position, velocity and acceleration profiles for backward sprinting. With the polynomial function in hand to capture and describe outfielders' action boundaries, an important piece of the puzzle for the further development of an affordance-based control strategy could be laid.

AFFORDANCE-BASED CONTROL IN RUNNING TO CATCH FLY BALLS

Overlooking the findings of Chapter 2 to 5, it is time to take stock. How do the present findings relate to form a full-blown affordance-based control model for fly-ball catching? How do the present findings add to the concept of affordance-based control as it was developed by Fajen in the context of braking? And what issues still need addressing for the further development of affordance-based control in fly-ball catching? These questions are at the core of the present thesis and will be discussed below, starting off with a further elaboration on the conceptual model on affordance-based control that has been put forward in Chapter 5.

Affordance-based control in running to catch fly balls was defined in Chapter 5 as the ratio of a_{ideal} over a_{max}, in which a_{ideal} is the rate of acceleration that will bring an outfielder to the right place in the right time to intercept a fly ball and in which a_{max} is the maximal rate of acceleration that an outfielder is able to bring about. In this, the characterization for a_{ideal} stems from a paper of Rozendaal and van Soest (2003). By considering the Optical Acceleration Cancellation strategy, Rozendaal and van Soest proposed a novel strategy for running to catch fly balls, which they termed: *Exact Optical Acceleration Cancellation*. They showed that the exact value for acceleration that would bring an outfielder to the right place in the right time (i.e. *ideal acceleration* in the present context) could be derived from the OAC-strategy (Rozendaal & Van Soest, 2003). Optical acceleration is a function of both the dynamics of the ball as well as the dynamics of the catcher-to-be, including the instantaneous acceleration of the catcher-to-be. Isolating this latter variable under the condition that optical acceleration should equal zero, provides the definition for the instantaneous acceleration that is required to successfully intercept a fly ball (i.e. a_{ideal}):

$$\ddot{x}_c = \ddot{x}_b - \frac{x_{bc}}{y_b}\ddot{y}_b - 2\dot{x}_{bc}(\frac{\dot{x}_{bc}}{x_{bc}} - \frac{\dot{y}_b}{y_b}) \quad (1)$$

Equation 1 (Rozendaal & van Soest, 2003) describes *ideal acceleration* as a function of the horizontal acceleration of the ball ($\ddot{x}_b$); the relative distance between the ball and the catcher (x_{bc}) and its first temporal derivative ($\dot{x}_{bc}$); and the vertical position of the ball (y_b) and its first ($\dot{y}_b$) and second ($\ddot{y}_b$) temporal derivative. Scaling this characterization of ideal acceleration to the maximal acceleration that an outfielder can bring about (Chapter 5) provides the current definition of affordance-based control, which is the ratio of a_{ideal} over

a_{max}. Whenever $\frac{a_{ideal}}{a_{max}} < 1$, it is still within the outfielders' action capabilities to get to the future interception location with the ball in time. Conversely whenever $\frac{a_{ideal}}{a_{max}} > 1$, the acceleration that the outfielder is *required* to bring about is greater than the maximal acceleration that the outfielder is *able* bring about; rendering the fly ball in question to be uncatchable. As such, the ratio of $\frac{a_{ideal}}{a_{max}}$ specifies the catchability of a fly ball; with values smaller than 1 specifying that a fly ball is catchable and values greater than 1 specifying that a fly ball is uncatchable. From here on out, this definition of affordance-based control in running to catch fly balls will be referred to as the *Affordance-Based Interception (ABI) strategy*.

In Chapter 5, a_{max} was characterized using a polynomial function of *current running speed*, *maximal running speed*, and *maximal overall running acceleration*. While this polynomial function proved highly effective in characterizing the data, the model specification appears to contain a singularity. The results from Chapter 5 suggest that a_{max} equals zero when the athlete is standing still, which is counterintuitive but also problematic in the context of modelling. When a_{max} were to be zero at standstill, the athlete would in theory remain stationary forever[1]. Mathematically speaking, another driving force would be needed to get the athlete moving. This is undesirable. There is however a deceptively simple solution to this paradoxical finding. In Chapter 5, an (infinite) number of polynomial equations have been identified that represent the data equally well. To deal with this plethora of model fits, Occam's razor was invoked, selecting the most parsimonious model. The most parsimonious model has its origin at (0,0), suggesting that a_{max} equals zero when running speed is null. As a characterization of athletes' running kinematics this seems off. The local positioning measurement system that was used to track participants' acceleration in Chapter 5 is inaccurate at low velocity (Ogris et al., 2012; Stevens et al., 2014). As such, based on the current findings, other (less parsimonious) model-equations might equally well be suited. Among these models are polynomial functions for which a_{max} is about half of the maximal overall acceleration that an athlete can produce at standstill. This would effectively solve the issue. Whereas further research on initial running accelerations should be conducted to exactly determine the maximal accelerations that outfielders in baseball can potentially bring about from standstill, literature on athletic sprinting suggests that athletes are potentially capable of producing great values of acceleration from standstill (Cross, Brughelli, Samozino, & Morin, 2017; Furusawa, Hill, & Parkinson, 1927; Greene, 1986; Hill, 1927; Pantoja, Saez De Villarreal, Brisswalter, Peyré-Tartaruga, & Morin, 2016; Samozino et al., 2016; Simperingham, Cronin, & Ross, 2016; Volkov & Lapin, 1979).

ADVANCES ON AFFORDANCE BASED CONTROL

The present model on affordance-based control is not merely a one-to-one extrapolation from the case of braking to the case of catching fly balls, it is an improvement on Fajen's original proposal in at least two respects. First, the portrayal of action boundaries is more realistic in the present context than in Fajen's original formalization of affordance-based control. Fajen formalized the concept of affordance-based control using a virtual reality

[1] In practice this would not be an issue as the outfielder is embedded in situations that are wider than just the act of catching. The outfielder is for instance also involved in the act of playing baseball. Situations evolve over time, calling for continuous adjustments that change the relationship among affordances, thus ultimately incentivizing the outfielder to start moving.

braking task. In this task, participants' action boundaries (i.e. the maximal strength of the brake of the car) were one-dimensional and instantaneous (by design). That is to say, the virtual braking task allowed participants to instantly instantiate the maximal strength of the brake of the car (however, see also: Fajen, 2008). When considering the real-world equivalent of this task, this seems unrealistic. In real-world braking, actors need time to reach the maximal rate of deceleration even if they slam the brakes. When braking forcefully, the rate of deceleration evolves to reach a maximum. Similarly, in the case of running to catch a fly ball: Outfielders cannot instantly instantiate their maximal running acceleration, especially not when they are not sure yet whether to run forwards or backwards to make the catch. Whereas this refinement in terms of action boundaries does not fundamentally change the concept of affordance-based control, it is important to keep in mind that action boundaries in real life situations are usually not 1-dimensional properties of an agent's action system. Researchers should be aware of this when further exploring the concept of affordance-based control and its applications.

The second improvement over Fajen's original proposition on affordance-based control is that the *Affordance Based Interception strategy* provides a control-law that might be used to guide behavior. In Fajen's original formalization of affordance-based control in braking, the ratio of d_{ideal} over d_{max} only specifies *whether* safe braking can be accomplished; *how* motorists should control the dynamics of the brake to accomplish this remains unresolved. From the ratio of d_{ideal} over d_{max} motorists know at all times whether braking is afforded, but not how one should brake to come to a safe stop. As such there is no control law that guides the motorist through the space of possibilities (cf. Harrison et al., 2016). The ABI-strategy not only provides a means of knowing *whether* it is still possible to make a catch but also provides a way of knowing *how* this can be accomplished.

Concealed within the ratio of ideal acceleration (a_{ideal}) over maximal acceleration (a_{max}) lies a control law that could guide an outfielder to the right place in the right time. This becomes clear when one considers the special case in which the ratio of a_{ideal} over a_{max} equals zero. For the ratio of a_{ideal} over a_{max} to equal zero, a_{ideal} must equal zero. And when a_{ideal} equals zero, the fielder is running at the constant velocity that would lead him or her to the future interception location with the ball in time[2]. Thus, running so as to null the ratio of a_{ideal} over a_{max} (by nulling a_{ideal}) would lead an outfielder to the right place in the right time to make a catch. What is particularly interesting about this is that when a_{ideal} equals zero, optical acceleration equals zero as well (Rozendaal & Van Soest, 2003). Which means that the ABI-strategy (firmly embedded within the affordance-based control framework) nicely fits the bulk of existing literature that has shown the OAC-strategy to be successful (e.g. Dienes & McLeod, 1993; Fink et al., 2009; McLeod & Dienes, 1996; Michaels & Oudejans, 1992). As such, the ABI-strategy provides a framework that combines both aspects of control and aspects of affordances in the continuous control of motor behavior. Thereby, the ABI-strategy provides a conceptual improvement over the OAC-strategy in that the ABI-strategy would also be able to account for the influence of the affordance of catchability on locomotor control in fly-ball catching.

[2] It should be noted that *any* value for the ratio of a_{ideal} over a_{max} smaller than 1 will lead an outfielder to the right place in the right time. However, the case in which the ratio of a_{ideal} over a_{max} equals 0 specifies that no further adjustments to locomotor velocity are needed to get to the right place in the right time.

EXTENSIONS TO THE GENERAL CASE

The control law that lies concealed within the ABI-strategy is not incidental to the case of running to catch fly balls. Indeed, the affordance-based control strategy that has been formulated for braking a car to a safe stop, can easily be adjusted to also include such a control law. The trick is to introduce an 'ideal state'. For the case of braking, that can be accomplished by adjusting the ratio of $\frac{d_{ideal}}{d_{max}}$ to also include the current rate of deceleration, d, providing the following equation:

$$\frac{d_{ideal} - d}{d_{max} - d} \qquad (2)$$

The affordance for safe braking as well as its embedded control law follow from Equation 2 as follows: When the current rate of deceleration equals the ideal rate of deceleration ($d_{ideal} == d$), the motorist is braking such that no additional braking adjustments are needed to come to a safe stop. Whenever this is the case, the ratio of $\frac{d_{ideal}-d}{d_{max}-d}$ will be equal to zero as well. Thus, nulling the ratio of Equation 2 will lead a motorist to come to a safe stop. Values between 0 and 1 specify that braking is still afforded but that the rate of deceleration should be increased. Conversely, values smaller than 0 specify that braking is afforded but that the rate of deceleration should be decreased to avoid coming to an early stop. Additionally, the affordance for safe braking can be directly perceived from the ratio given in Equation 2. When ideal deceleration is smaller than maximal deceleration, the ratio of $\frac{d_{ideal}-d}{d_{max}-d}$ will be smaller than 1, specifying that it is still within the action possibilities of the motorist to bring the car to a safe stop. Conversely when ideal deceleration is greater than maximal deceleration, the ratio of $\frac{d_{ideal}-d}{d_{max}-d}$ will be greater than 1, specifying that it is no longer within the action possibilities of the motorist to bring the car to a safe stop. Equation 2 illustrates that a formalization of affordance-based control that provides both a control law and a way to directly perceive action possibilities is not incidental to the fly ball paradigm, but can also be identified for other paradigms, like the braking paradigm.

Fajen (2007) readily acknowledged that his original formalization of affordance-based control did not provide a specific account that explains *how* an actor might control his or her behavior within the limits of his or her action possibilities. Fajen's affordance-based control framework on braking provided an account on how motorists could perceive the limits of their action possibilities, yet no specific account was provided on how motorists might guide their behavior within these limits. As such, one of the merits of the present thesis is the illustration of the fact that affordance-based control need not be limited to the mere specification of affordances, but that affordance-based control can potentially encompass a rationale for control as well.

Recently, Harrison, Turvey and Frank (2016) proposed a different solution to address the issue of control within the affordance-based control framework. Following Fajen's original suggestion of 'soft-constraints' (Fajen, 2005b, 2005c, 2007a), they provided a dynamical description of affordance-based control by introducing soft-constraints that influence braking behavior, such as 'preference' and 'comfort': A motorist that is in a hurry might brake more abruptly than someone that puts a high value on comfort. Modelling these constrains using a proximity function, the soft-constraints exert influence for as long as the hard-constraint is not violated. The closer the motorist is to reaching his or her action boundary (i.e. hard constraint), the smaller the influence of the soft-constraint becomes. The combination of soft-constraints and hard-constraints can be modelled to provide a unique path through the space of possibilities.

While the rationale for using a combination of soft-constraints and hard-constraints to collapse possibility into actuality is mathematically sound (Harrison et al., 2016), its implementation in the fly ball paradigm would run counter to many empirical studies that have shown outfielders to run such that optical acceleration is effectively nulled throughout the greatest part of their running movement (e.g. Dienes & McLeod, 1993; Fink et al., 2009; McLeod & Dienes, 1996; Michaels & Oudejans, 1992). The implementation of soft-constraints within the fly ball paradigm would result in optical-acceleration profiles that will in fact be nonzero throughout the greater part of an outfielder's running movement. As such, the present proposal for affordance-based control seems more fitting: Outfielders are incentivized to null the ratio of *ideal acceleration* over *maximal acceleration* to get to the right place in the right time, likely resulting in optical-acceleration profiles that naturally align with the existing body of literature on running to catch fly balls.

LIMITATIONS AND FUTURE RESEARCH

Developing a full-blown affordance-based control strategy for running to catch fly balls proved more challenging than was expected. While the present thesis provides impetus to the development of such a strategy, a number of issues still remain. Some of which relate to methodology (e.g. having determined *maximal acceleration* without participants having to make a catch) and others of which relate to aspects of affordance-based control that have remained underexposed (e.g. informational specification) or untested (e.g. the ABI-model itself). In the next couple of paragraphs, the most pressing issues concerning the further development of a full-blown affordance-based control strategy for running to catch fly balls will be discussed.

First and foremost, the affordance-based control strategy put forward in this thesis remains untested. While the ABI-strategy seems conceptually promising, its empirical validity needs to be determined still. A possible way to approach this would be to focus on outfielders' judgments of catchability once more, examining whether judgments of catchability align with the potential use of the ABI-strategy. To do this, an experimental design similar to that of Fink, Foo and Warren (2009) might be used. Fink and colleagues studied the potential use of the OAC-strategy by having participants run to intercept fly balls in virtual reality. By perturbing the vertical motion of fly balls mid-flight, the effect of optical acceleration on locomotor behavior could be examined. A similar rationale might be used to test whether outfielders' judgments of catchability align with the use of the ABI-strategy. Employing virtual reality in much the same way as Fink and colleagues did, the motion of the ball could be perturbed mid-flight to manipulate catchability. By having participants indicate the moment they perceive a fly ball to be no longer catchable, a temporal pattern of perceptual judgments could be obtained. From the use of the ABI-strategy, one would expect that the timing of participants indicating a fly ball to be uncatchable would be consistent with the timing of *ideal* *acceleration* exceeding *maximal acceleration*. Finding this to be the case would provide crucial support in favor of the ABI-strategy.

Another way to assess the empirical validity of the ABI-strategy, would be to examine whether outfielders are more likely to increase their rate of acceleration when ideal acceleration is close to maximal acceleration (cf. Figure 6 of Fajen, 2005a). Fajen showed for braking a car to a safe stop that motorists tend to *increase* the rate of deceleration when ideal deceleration is close to maximal deceleration, whereas braking adjustments were much more variable when ideal deceleration was low. This finding is particularly interesting as Fajen only analyzed data-points in which no additional braking adjustments had to be made to brake the car to a safe stop (Fajen, 2005a). This illustrates that motorists are sensitive to their action boundaries in a way that cannot be explained by simple error-nulling (information-based control) strategies, as those strategies would predict no additional braking adjustments whenever the current rate of deceleration is sufficient to come to a stop. Finding that outfielders in baseball would do the same in terms of *acceleration* when running to make an attempted catch would provide support for the use of the ABI-strategy. To examine whether this would be the case, an experiment could be designed in which outfielders are invited to intercept a range of fly balls, among which is a number of fly balls that require them to run at a rate of acceleration that is close to their maximal rate of acceleration. Subsequently, the likelihood of participants increasing their rate of acceleration might be examined in much the same way as Fajen did for the case of braking (Fajen, 2005a, 2007a). Finding that participants are more likely to make positive adjustments to their rate of acceleration for greater values of a_{ideal}, while no such adjustments would be required to make the catch, would provide support for the use of the ABI-strategy in running to catch fly balls. Such behavior would indicate that outfielders are sensitive to their action boundaries in a way that cannot be accounted for by the OAC-strategy.

Though, for the ABI-strategy to serve as the basis for guiding locomotion in running to catch fly balls, the ratio of a_{ideal} over a_{max} must be perceptually available to the catcher-to-be. That is, outfielders must be able to pick up changes in the ratio of a_{ideal} over a_{max} to guide locomotion. At this point, the ratio of a_{ideal} over a_{max} has only been specified in terms of spatial variables: *Ideal acceleration* is a function of the current motion of the ball and the current state of the outfielder (Equation 1) and *maximal acceleration* is a function of an outfielder's current running velocity, maximal running velocity and maximal overall running acceleration (Chapter 5). The question is: How can the ratio of a_{ideal} over a_{max} be specified in terms of optical variables that are available to an outfielder? In answering this question, it should be noted that maximal acceleration need not be optically specified in its own right. Rather, ideal acceleration might be expressed in units relative to maximal acceleration so that the case of $\frac{a_{ideal}}{a_{max}} == 1$ consistently separates catchable from uncatchable fly balls. This would require outfielders to be properly *calibrated* (Fajen, 2005c, 2007b). That is, for accurate perception of catchability, outfielders must not over- or underestimate the maximal rate of acceleration that they can bring about. Underestimation of one's action capabilities would compress the metric for $\frac{a_{ideal}}{a_{max}}$, leading an outfielder to perceive certain fly balls to be uncatchable that are in fact catchable while the reverse holds true for an overestimation of one's action capabilities.

For the ABI-strategy to serve as the basis for locomotor control in running to catch fly balls, outfielders must be calibrated to an action boundary that is dependent on running velocity and is thereby nonlinear and dynamic (Chapter 5). It might be argued that such calibration is difficult or even impossible. Yet, recent evidence in the context of braking a car to a stop, has shown that motorists are well able to adapt to nonlinear brake-dynamics. Motorists are shown to adapt to brake dynamics for which the rate of deceleration was proportionally dependent on both pedal position and current velocity (Fajen, 2008). This finding supports the idea that outfielders in baseball might also be able to control their locomotor behavior relative to an action boundary that is nonlinearly dependent on their current running velocity (see also Chapter 5).

While perceptual-motor calibration alleviates the burden of optically specifying the ratio of a_{ideal} over a_{max}, it does not solve the problem. The (optical) information specifying a_{ideal} remains undetermined. At present, there is no account that specifies how *ideal acceleration* might be optically available to an outfielder. To shed light on this issue, decision tree analysis, a popular tool in machine learning, might be employed. Weber and Fajen (2015) successfully used this technique to characterize the optical information that was used by motorists in a collision-avoidance task. With decision tree analysis, a data driven approach can be taken to uncover the mapping from optical information to action in performing a certain task. The procedure works by rule induction, combining optical variables into different combinations (of ranging complexity), to arrive at a control strategy that is most likely to explain a set of observations. Once support has been obtained for the use of the ABI-strategy in running to catch fly balls, decision tree analysis might be employed to shed light on the optical variables that might be involved in the specification of the ratio of a_{ideal} over a_{max} in running to catch fly balls.

Finally, closing off with a methodological issue, the macroscopic model on sprint running that has been proposed in Chapter 5 to characterize outfielders' action boundaries in running to catch fly balls has been developed without participants actually having to make a catch. It might be argued that this limits the validity of the model with respect to actual fly-ball catching. One elegant way to tackle this concern, would be to employ Generalized Additive Modelling in a direct comparison of kinematic data from simple sprint running with kinematic data from running to intercept a fly ball. An experiment could be designed in which participants would be required to perform sprints in two different conditions. In the first condition, participants would simply be required to cover different distances as fast as possible. In the second condition, participants would still be required to cover those very same distances but now they have to do so in order to intercept a fly ball that is just barely catchable. Directly comparing kinematic data from these two conditions might determine the validity of the macroscopic model presented in Chapter 5 for the fly ball paradigm. As a by-product, this experimental design might also shed light on the 'finish-line effect' that has been observed in Chapter 5: Participants have consistently been shown to slow down when nearing the finish line. With the experiment that is suggested here, it might be examined whether such behavior is specific to athletic sprint running, or whether similar behavior is displayed in running to catch a fly ball.

CONCLUSION

The concept of affordance-based control has bridged the divide between two major branches of perception-action research, with on the one hand a branch that focuses heavily on the perception of affordances (e.g. Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Cesari, Formenti, & Olivato, 2003; Cesari & Newell, 1999, 2000; Mark, 1987; Newell, McDonald, & Baillargeon, 1993; Warren, 1984; Warren & Whang, 1987) and on the other hand a branch that focuses heavily on the continuous control of visually guided action (e.g. Chapman, 1968; Fajen, 2001; Fajen & Warren, 2004; Kim & Turvey, 1999; Kim, Turvey, & Carello, 1993; Lee, 1976; McBeath, Shaffer, & Kaiser, 1995; McLeod et al., 2006; Michaels & Oudejans, 1992; Peper, Bootsma, Mestre, & Bakker, 1994; Wann & Land, 2000; Yilmaz & Warren, 1995). With the development of the concept of affordance-based control, Fajen has made a conceptual framework available for understanding how actors are able to account for affordances in controlling motor behavior (Fajen, 2005c, 2005b, 2005a, 2007a). While the focus of this dissertation has been on intercepting fly balls, the implications of this research reach beyond the fly ball paradigm. Most notably, this thesis provides a first step towards truly incorporating aspects of control within an affordance-based control framework. Whereas Fajen's original proposal on affordance-based control was missing a control law for (braking) behavior, the current conceptualization of affordance-based control in catching provides a way to guide behavior while also accounting for the affordances of the situation. Thus putting 'control' back into 'affordance-based control'.

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APPENDICES

SUMMARY

The concept of *affordance-based control* provides a theoretical framework for characterizing control of motor behavior in everyday-life and sports, such as braking a car to a safe stop and running to catch a baseball. It emphasizes the role of *affordances*, or action possibilities, in the visual guidance of action. The aim of this thesis is to develop a model of affordance-based control within the *fly ball paradigm* (see below). Thereby, this thesis aims to contribute to the further development of the concept of affordance-based control in general.

The fly ball paradigm concerns the case of an outfielder in baseball running to intercept a ball batted high into the air, colloquially known as a *fly ball*. Getting to the future interception location with the ball in time is not a trivial task and requires meticulous locomotor control. This control-aspect of running to catch fly balls has received considerable scientific attention. The affordance-aspect of this task however, which concerns the influence of *catchability* on outfielders' locomotor behavior, has remained underexposed. Still, the potential influence of the affordance of catchability on locomotor control might be profound. An intuitive example of this might be seen from the case in which an outfielder is presented with a fly ball that is clearly uncatchable. In this scenario, instead of running in vain to make an attempted catch, the outfielder might rather have a teammate make the catch. Other examples exist that illustrate the potential influence of the affordance of catchability on locomotor control in running to catch fly balls. Yet, existing (information-based) control strategies do not account for the affordance of catchability and might therefore have a limited reach when it comes to characterizing outfielders' locomotor behavior. Thus, putting affordances centerstage, this thesis aims to develop an affordance-based control strategy for the visual guidance of action in the fly ball paradigm.

This thesis starts off by examining the gaze behavior that outfielders display while running to make a catch. Affordance-based control, just like any other prospective-control theory, is contingent on the continuous visual guidance of action. In case of the fly ball paradigm, one would expect an outfielder to keep close to continuous visual contact with the ball to control locomotor behavior. In **Chapter 2,** this hypothesis is put to the test. In an experimental setting, participants were required to intercept fly balls projected behind or in front of the initial position of the participant. The projected fly balls could be either catchable or uncatchable. Participants were equipped with a mobile gaze tracker to examine their gaze behavior throughout the attempted catch. Previously, gaze behavior had only been studied for fly balls projected within an outfielder's catchable range, Chapter 2 adds to this by also examining participants' gaze behavior for fly balls that are projected beyond their catchable range. It is shown that participants foveated the ball nearly exclusively, both for catchable and uncatchable fly balls. This was found to be the case for fly balls projected behind the initial position of the participant as well as for fly balls projected in front. Having established that participants continuously tracked the ball allowed for the next step in the development of an affordance-based control strategy for running to catch fly balls.

Chapter 3 examines whether the dominant (information-based) control strategy for running to catch fly balls, the Optical Acceleration Cancellation (OAC)-strategy, can be used as a vehicle for the development of an affordance-based control strategy for the fly-ball paradigm. Specifically, it is examined in Chapter 3 whether the OAC-strategy can be extended to also include the affordance of catchability. Theoretically, the OAC-strategy would allow for the

affordance of catchability to be perceived under two distinct circumstances. First, a fly ball might be perceived as catchable when the outfielder is running such that optical acceleration is successfully nulled. Second, a fly ball might be perceived as uncatchable when optical acceleration is nonzero and the fielder is already running at maximal velocity. If outfielders' judgments of catchability align with these predictions, the OAC-strategy might well serve as a basis for affordance-based control in running to catch fly balls. To test this hypothesis, participants were challenged to intercept both catchable and uncatchable fly balls, projected either behind or in front of their initial position. For this experiment, participants were empathically instructed to call 'no' the instant they perceived a fly ball to be uncatchable. By analyzing participants' running speeds (and accelerations) at the moment of calling 'no' it was examined whether judgments of (un)catchability were likely to be based on the use of the OAC-strategy. It was found however, that participants' running speeds and -accelerations were often far from maximal. In fact, participants were sometimes even standing still while judging a fly ball to be uncatchable. Taken together, the findings from Chapter 3 indicate that outfielders are unlikely to solely rely on a strategy of nulling optical acceleration to judge the catchability of a fly ball.

Chapter 4 is specifically dedicated to uncovering the affordance of catchability, that is: What renders a fly ball to be either catchable or uncatchable? And are outfielders able to accurately perceive the catchability of a fly ball? Both inquiries are crucial to the development of an affordance-based control strategy for running to catch baseballs. If fielders prove unable to perceive the affordance of catchability, developing an affordance-based control strategy seems unwarranted. However, if fielders are indeed capable of perceiving the affordance of catchability, then the question is: How can this affordance be characterized? To shed light on these two issues, an experiment was designed similar to the experiment of Chapter 3. Participants were required to intercept fly balls that could either be catchable or uncatchable, projected either behind or in front of their initial position. However, in contrast to the experimental design presented in Chapter 3, this particular design consisted of two different tasks. In the *catching task*, participants were required to make a run for each and every fly ball, even if they perceived it to be uncatchable. In the *judging task*, participants were required to call 'no' the instant they perceived a fly ball to be uncatchable and were then allowed to stop running (just as in the study reported in Chapter 3). Mixed-effects regression analysis was used on data from the first condition to shed light on the make-up of the affordance of catchability. From this analysis, five behaviorally relevant agent-environment factors were identified, which together accounted for 84.4% of the variance in catching performance. With this regression model, catchability could also be predicted for individual trials in the judging task. By comparing predicted catchability with judged catchability, participants' ability to reliably judge the catchability of a fly ball could be assessed. It was shown that participants were indeed accurate in judging the catchability of a fly ball, thus prompting the further development of an affordance-based control account.

Chapter 5 presents the last empirical study of this thesis. In Chapter 5, the action boundary for running to catch fly balls is examined. In doing so, a closer look is taken at one of the variables that surfaced in Chapter 4's analysis on the affordance of catchability: i.e. '*locomotor range*'. In Chapter 4, locomotor range (which was taken to be the greatest distance that a participant was able to cover in any of the trials during the experiment) emerged as the best predictor on the agent-side of the affordance of catchability. Locomotor range captured more variance than (the linear combination of) maximal running speed and maximal running acceleration, which brought a couple of questions to bear. First off, how can the greatest distance that an outfielder in baseball is able to cover over time be characterized? Second, is the total distance that an outfielder has to cover to intercept a fly ball of influence on the kinematic profiles that are displayed? And finally, somewhat on a tangent, what would be the faster locomotor strategy for catching a fly ball that is bound to fly overhead? Making a quick turn, running forwards while looking over the shoulder, or simply running backwards? These three questions are crucial in the development of an affordance-based control strategy. To address these issues, an experiment was designed in which participants were required to perform maximal-effort sprints in different fashions (forwards, backwards, with turn) over different distances. Participants' kinematic profiles were recorded using the Local Positioning Measurement (LPM) system. It was shown that the locomotor range of an outfielder was best characterized by a nonlinear combination of maximal running velocity, maximal running acceleration and current running speed. Target distance was of no influence on this relationship. Furthermore, it was found that it would always be faster, even for very short sprints, to make a turn and run forwards than to simply run backwards. Chapter 5 closes off with the proposition of an affordance-based control model for running to catch fly balls.

The epilogue, **Chapter 6**, considers the pros and cons of the conceptual model proposed in Chapter 5. In this final chapter, a plea is made for pursuing the further development of the concept of affordance-based control, albeit in a different fashion than was originally proposed by Fajen. The conceptual model presented in Chapter 5 envisions an affordance-based control strategy for running to catch fly balls that combines aspects of control (*information-based control*) with aspects of affordances (*affordance-based control*), thereby adding to Fajen's original proposal. The argument is made that this should be the way to go for characterizing motor control in everyday-life and sports.

SAMENVATTING

Het concept van *affordance-based control* biedt een theoretisch kader waarmee de motorische contole voor bewegingssturing gekarakteriseerd kan worden. Veel handelingen in het leven van de alledag en sport vergen nauwgezette motorische controle: *sprinten* om een bal te onderscheppen en *remmen* om een auto tot stilstand te brengen zijn slechts twee voorbeelden hiervan. De nadruk in affordance-based control ligt op het concept van *affordances*. Affordances zijn individu-specifieke actiemogelijkheden die bepalend zijn voor de wijze waarop het individu diens handelen controleert. Het voornaamste doel van dit proefschrift is om een affordance-based control model te ontwikkelen specifiek voor het *fly ball paradigma* (zie onderstaand). Daarmee is de hoop dat dit proefschrift in bredere zin zal bijdragen aan de ontwikkeling van het concept van affordance-based control.

Het fly ball paradigma, zoals hierboven aangehaald, is een wetenschappelijke beschouwing van een situatie waarin een *outfielder* in baseball sprint om een *fly ball* (een hoge boogbal) te vangen. Sprinten om een fly ball te onderscheppen is geen triviale taak. Nauwgezette motorische controle is vereist om op het juiste moment op de juiste plaats uit te komen. Hoewel veel aandacht in de literatuur uit is gegaan naar de motorische controle die vereist is om een fly ball te onderscheppen, is het affordance-aspect lange tijd onderbelicht gebleven. Terwijl de affordance voor vangbaarheid mogelijk van grote invloed is op de motorische controle die een outfielder uitoefent. Een intuïtief voorbeeld hiervan is bijvoorbeeld het geval waarin een outfielder wordt geconfronteerd met een fly ball die duidelijk niet vangbaar is. In dit scenario zal de outfielder waarschijnlijk niet een tevergeefse poging ondernemen om de bal te onderscheppen. In plaats daarvan zal de outfielder wellicht een teamgenoot aansporen om de betreffende bal te vangen. Hoewel dit voorbeeld niet uniek is in de wijze waarop het de potentiële invloed van de affordance voor vangbaarheid op motorische controle illustreert, houden bestaande theorieën hier geen rekening mee. In effect betekent dit dat bestaande theorieën mogelijk niet toereikend zijn in de karakterisering van het sprintgedrag van outfielders. Zodoende wordt in dit proefschrift de affordance voor vangbaarheid centraal gesteld met als doel het ontwikkelen van een affordance-based controle strategie voor de visuo-motorische controle van sprinten in het fly ball paradigma.

Het eerste experimentele hoofdstuk van dit proefschrift is gericht op het kijkgedrag van outfielders tijdens het onderscheppen van fly balls. Voor prospectieve controle strategieën, zoals affordance-based control, wordt verondersteld dat bewegingssturing gecontroleerd wordt onder geleiding van continue visuele input. In de context van het fly ball paradigma wordt dus verwacht dat een outfielder continu visueel contact met de bal houdt om diens loopgedrag te controleren. In hoofdstuk 2 wordt deze hypothese getoetst. Proefpersonen werden geacht in een experimentele setting fly balls te onderscheppen die zowel vóór als áchter de startpositie van de proefpersoon konden landen. De betreffende fly balls konden zowel vangbaar als onvangbaar zijn. Voor het experiment werden de proefpersonen uitgerust met een mobiele oogtracker waarmee hun kijkgedrag onderzocht kon worden. Voorheen is het kijkgedrag van outfielders enkel onderzocht voor fly balls die vangbaar waren. Met het experiment uit hoofdstuk 2 worden deze bevindingen uitgebreid naar de situatie waarin fly balls zowel vangbaar als onvangbaar kunnen zijn. Uit de bevindingen van hoofdstuk 2 blijkt dat outfielders vrijwel exclusief hun blik op de bal gericht houden terwijl ze rennen om een bal te onderscheppen. Dit bleek het geval voor vangbare- en onvangbare ballen, ongeacht of deze vóór of áchter de initiële positie van de proefpersoon geprojecteerd werden. Met de

bevindingen uit hoofdstuk 2 is een cruciale assumptie onderliggend aan het gebruik van affordance-based control getest. Door vast te stellen dat outfielders inderdaad continu naar de bal kijken voor het onderscheppen van een fly ball, kon de volgende stap gezet worden in het ontwikkelen van een affordance-basded controle strategie voor het vangen van fly balls.

In hoofdstuk 3 wordt onderzocht of de *Optical Acceleration Cancellation* (OAC) strategie, de dominante controle strategie in het fly ball paradigma, als uitgangspunt kan dienen voor de ontwikkeling van affordance-based control strategie. De OAC-strategie omvat nog niet het affordance-aspect voor het vangen van fly balls, in hoofstuk 3 wordt er onderzocht of de OAC-strategie aangepast kan worden om alsnog het concept van affordances te omvatten. Vanuit de theoretische kaders van de OAC-strategie is een outfielder in staat om de vangbaarheid van een bal onder twee specifieke condities waar te nemen. Allereerst zou een fly ball als *vangbaar* waargenomen kunnen worden op het moment dat de outfielder zodanig rent dat optische acceleratie gelijk is aan nul. Daarentegen zou een fly ball als *onvangbaar* waargenomen kunnen worden op het moment dat de outfielder op diens maximale snelheid rent én optische acceleratie ongelijk is aan nul. Als blijkt dat outfielders de vangbaarheid van een fly ball inschatten op een manier die consistent is met deze twee condities, dan zou de OAC-strategie als basis kunnen dienen voor het ontwikkelen van een affordance-based controle strategie. Om te toetsen of vangbaarheid inderdaad alleen waargenomen wordt wanneer aan één van beide condities wordt voldaan is een experiment ontwikkeld waarin outfielders zowel vangbare als onvangbare ballen moesten onderscheppen. Wanneer een proefpersoon een bal als niet vangbaar beschouwde, werd hij/zij geacht direct 'nee' te roepen. Net als in de experimentele setting van hoofdstuk 2, werden de fly balls zodanig geprojecteerd dat deze zowel vóór als áchter de startpositie van de proefpersoon terecht zouden kunnen komen. Omdat de onvangbaarheid van een fly ball vanuit het gebruik van de OAC-strategie alléén waargenomen kan worden wanneer een outfielder op diens maximale snelheid loopt, is onderzocht wat de loopsnelheid was van de proefpersonen op het moment van 'nee'-roepen. De bevindingen uit hoofdstuk 3 laten duidelijk zien dat noch de loopsnelheid noch de acceleratie van proefpersonen maximaal was op het moment van 'nee'-roepen. Soms stonden proefpersonen zelfs stil terwijl ze aangaven dat een bal onvangbaar was. Deze bevindingen wijzen erop dat de vangbaarheid van een fly ball onder meer omstandigheden waargenomen kan worden dan op basis van de OAC-strategie verwacht wordt. Zodoende lijkt het onwaarschijnlijk dat outfielders enkel en alleen gebruik maken van de OAC-strategie om de vangbaarheid van een bal in te schatten, wat aanleiding geeft tot de ontwikkeling van een nieuwe strategie die rekening houdt met de beoogde invloed die de affordance voor vangbaarheid kan hebben op het vangen van fly-balls.

In hoofdstuk 4 wordt de affordance voor vangbaarheid verder onderzocht: wat bepaalt de vangbaarheid van een bal? En zijn outfielders in staat om de vangbaarheid van een bal accuraat in te schatten? Beide vraagstukken zijn cruciaal in de verdere ontwikkeling van een affordance-based controle strategie. Als blijkt dat verrevelders niet in staat zijn om de vangbaarheid van een bal (accuraat) in te schatten, dan lijkt het niet gegrond om de verdere ontwikkeling van een affordance-based controle strategie na te jagen. Als echter blijkt dat outfielders wel degelijk in staat zijn om een accurate inschatting te maken van de vangbaarheid van een fly ball, dan is de vraag: waardoor wordt de vangbaarheid van een fly ball bepaald? Om dit te onderzoeken is een experiment uitgevoerd waarvan de experimentele setting gelijkend is aan die van hoofdstuk 3. Echter, in tegenstelling tot het experiment uit hoofdstuk 3, bestond het experiment uit hoofdstuk 4 uit twee verschillende condities: een *vangtaak* en een *inschattingstaak*. Voor de vangtaak werd proefpersonen gevraagd om ongeacht de vangbaarheid van de bal hun uiterste best te doen om deze te toch onderscheppen. Voor de inschattingstaak werd tevens van de proefpersonen verwacht dat ze hun uiterste best deden om de bal te onderscheppen, echter mochten de proefpersonen in de inschattingstaak 'nee' roepen als ze een fly ball als onvangbaar beschouwden. Ze mochten dan stoppen met rennen. Om te bepalen welke factoren gerelateerd zijn aan de vangbaarheid van een bal, is mixed-effects regressie analyse gebruikt op de data van de eerste conditie. Uit deze analyse is gebleken dat de variantie in de vangbaarheid van fly balls voor 84,4% gekarakteriseerd kon worden. Deze karakterisering kon gemaakt worden aan de hand van vijf factoren, gerelateerd aan de baan van de bal en aan de (locomotorische) kwaliteiten van de proefpersoon. Het regressiemodel uit conditie 1 is vervolgens gebruikt om te bepalen of outfielders in staat zijn om de vangbaarheid van een bal nauwkeurig in te schatten. Door middel van het regressiemodel kan op individuele basis de vangbaarheid van fly balls bepaald worden. Zodoende kon voor conditie 2 een vergelijking gemaakt worden tussen de voorspelde waardes van vangbaarheid en de vangbaarheid zoals ingeschat door de proefpersonen. Hieruit is gebleken dat proefpersonen inderdaad in staat zijn om de vangbaarheid van een bal accuraat in te schatten. De bevindingen van hoofdstuk 3 geven meer grip op de affordance voor vangbaarheid en nodigen uit tot de verdere ontwikkeling van een affordance-based controle strategie voor het vangen van fly balls.

In hoofdstuk 5 wordt de laatste empirische studie van dit proefschrift gepresenteerd. Uit de bevindingen van hoofdstuk 4 is gebleken dat proefpersonen verschillen in hun kwaliteit om ballen succesvol te onderscheppen en dat dit verschil voornamelijk te weiden in aan verschillen in het 'locomotorisch bereik'. Het 'locomotorisch bereik' van een proefpersoon werd in hoofdstuk 4 bepaald als de grootste afstand die een proefpersoon tijdens het experiment in één trial af heeft gelegd. Deze onconventionele maat presteerde in het regressie model beter dan (de lineaire combinatie van) maximale snelheid en -versnelling, twee maten die in de literatuur genoemd worden als verklarende factoren. Met deze bevinding ontstonden er een drietal nieuwe vragen voor de verdere ontwikkeling van een affordance-based control model. Hoe kan de grootste afstand die een outfielder binnen een bepaalde tijd af kan leggen gekarakteriseerd worden? Is de totale afstand die een outfielder af moet leggen van invloed op de ontwikkeling van de loopsnelheid van een outfielder over de tijd? En tot slot, wat is de snelste loopstrategie voor outfielders die een bal proberen te onderscheppen die achter hun startpositie zal landen? – Is het sneller om simpelweg achterwaarts te sprinten, of is het sneller om, na een snelle draai, voorwaarts te sprinten? Deze drie vragen zijn cruciaal voor de verdere ontwikkeling van een affordance-based control strategie. In hoofdstuk 5 wordt een simpel experiment gepresenteerd wat deze vraagstukken adresseert. Proefpersonen werden in een experimentele setting gevraagd om verschillende type sprints uit te voeren (voorwaarts, achterwaarts, -mét draai) over verschillende afstanden. Tijdens het experiment werden de kinematische sprintprofielen van de proefpersonen geregistreerd met het '*Local Positioning Measurement*' (LPM) systeem, wat fungeert als een lokaal GPS-systeem. De resultaten van dit experiment laten zien dat het locomotorisch bereik van de outfielder het best gekarakteriseerd kan worden aan de hand van een nonlineaire combinatie van een outfielders' momentane loopsnelheid, maximale loopsnelheid en maximale acceleratie. Voor deze nonlineaire relatie bleek de totale afstand die afgelegd diende te worden niet van invloed. Ten slotte, in antwoord op de derde hoofdvraag, blijkt dat achterwaarts sprinten altijd langzamer is dan een snelle draai maken en voorwaarts sprinten, óók over zeer korte afstanden. Mede aan de hand van de empirische bevindingen uit eerdere hoofdstukken, sluit hoofdstuk 5 af met de presentatie van een conceptueel model voor affordance-based control voor het vangen van fly balls.

In hoofdstuk 6, de epiloog, worden de voor- en nadelen van het in hoofdstuk 5 gepresenteerde conceptuele model besproken. In de epiloog wordt er gepleit voor de verdere ontwikkeling van het concept van affordance-based control. Het conceptuele model zoals gepresenteerd in hoofdstuk 5 omvat zowel het controle-aspect (information-based control) als het affordance-aspect (affordance-based control) voor het vangen van fly balls. Daarmee wijkt het af van Fajen’s oorspronkelijke voorstel waarvoor alléén het affordance-aspect expliciet uitgewerkt werd. In de epiloog wordt er gepleit voor een vorm van affordance-based control waarin zowel de affordance-aspecten als de controle-aspecten geëxpliciteerd zijn. In bredere zin wordt het pleidooi gemaakt dat motorische controle in alledaagse activiteiten en in sportieve activiteiten het best gekarakteriseerd kunnen worden aan de hand va het conceptuele model zoals dat in dit proefschrift wordt voorgesteld.

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"No man can reveal to you aught but that which already lies half asleep in the dawning of your knowledge.

The teacher who walks in the shadow of the temple, among his followers, gives not of his wisdom but rather of his faith and his lovingness.

If he is indeed wise he does not bid you enter the house of his wisdom, but rather leads you to the threshold of your own mind."

-Khalil Gibran, The Prophet-

To Frank Zaal, the teacher who led me to the threshold of my mind. Dear Frank, you have always been very diligent, devoted and patient in supporting me getting the best out of myself. You were always there for council, inspiration and guidance, whether it was science, work or life in general. Your lessons have been extraordinarily valuable to me and have shaped me to become the scientist I am today. You have been a mentor and a friend. And for that, I am ever grateful!

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CURRICULUM VITAE

Dees Postma was born on the first of October, 1989. In 2008, he graduated from high school after which he moved to Groningen to study Human Movement Sciences. It was in this period that his love for visual perception took off. During his Bachelor's, Dees started consiously cultivating and growing this love, taking extra classes on visual perception, motor control and neurophysiology. Besides that, Dees also picked up photography at the *Fotoacademie*, thereby following his lifelong passion for photography and the visual arts. This, heartfelt and profound interest in the visual sciences led Dees to write a research proposal on visual perception in baseball for his bachelor graduation project. The proposal was honored and the project proved successful as the experimental study would ultimately be published in a high-impact journal. This publication put Dees on the fast-track for his Master-PhD trajectory at the Center for Human Movement Sciences in Groningen. Dees obtained his Master's degree in Sport Sciences with *cum laude* in 2014. During his Master's, Dees was an active board member for 'Love to Know' (one of the competing teams for NWO's academic year prize), worked as a student teacher for a Master's course and continued his work as a freelance photographer. All of this culminated in Dees winning the *Groningen University Student Excellence Award (GUF-100 prize)*.

During his PhD, Dees studied the relationship between visual perception and motor control. Specifically, Dees was interested to examine how athletes are able to perceive and account for their own action capabilities in controlling their motor behavior. During his time as a PhD-student, Dees actively focused on honing his teaching skills; continuing his work as a student teacher at the center for Human Movement Science and later on by working as a lecturer in Healthcare Technology at the University of Applied Sciences Rotterdam.

Currently, Dees works as a post-doctoral researcher on Human Media Interaction Design at the University of Twente. Specifically, Dees is working on the *Smart Sports Exercises* project, a multidisciplinary, ZonMw funded, project that aims to improve volleyball practice through the use of interaction technology, in this case a next-generation interactive sports court. Building on core principles from both the field of human movement science and interaction design, Dees aims to develop digital-physical training exercises that are more engaging and effective than traditional volleyball drills.

SCIENTIFIC OUTPUT

Postma, D. B. W., den Otter, A. R., & Zaal, F. T. J. M. (2014). Keeping your eyes continuously on the ball while running for catchable and uncatchable fly balls. *PloS One*, *9*(3), e92392. doi:10.1371/journal.pone.0092392

Postma, D. B. W., Lemmink, K. A. P. M., & Zaal, F. T. J. M. (2018). The affordance of catchability in running to intercept fly balls. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(9), 1336–1347. doi:10.1037/xhp0000531

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Zaal, T.J.M., de Poel, H.J., Postma, D.B.W., Otten, E. & Pepping, G.-J. Movement. Initiation Patterns are Consistent with the Use of Optical Acceleration in Running to Catch Fly Balls, forthcoming

Postma, D.B.W., Martijn B. Wieling, Lemmink, K.A.P.M. & Zaal, T.J.M. Distance over Time in a Maximal Sprint: Understanding Athletes' Action Boundaries in Sprinting, forthcoming

CONFERENCE CONTRIBUTIONS

Direct Perception of Catchability, Postma, D.B.W. & Zaal, F.T.J.M. *Poster presentation at the 4th International Congress on Complex Systems in Sports and Healthy Aging, October 2014, Groningen, The Netherlands*

Perception of Catchability of Fly Balls, Postma, D.B.W. & Zaal, F.T.J.M. *Oral presentation at the 18th International Conference on Perception & Action, July 2015, Minneapolis, The United States of America*

Intercepting Fly Balls: The Affordance of Catchability, Postma, D.B.W., Lemmink, K.A.P.M. & Zaal, F.T.J.M. *Oral presentation at the 14th European Workshop on Ecological Psychology, July 2016, Groningen, The Netherlands*

Towards Affordance-Based Control in Catching Fly Balls: The Affordance of Catchability, Postma, D.B.W. & Zaal, F.T.J.M. *Poster presentation at the 17th annual meeting of the Vision Sciences Society, May 2017, Tampa, The United States of America*